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DESCRIPTION OF AN ENERGY MANAGEMENT SYSTEM FOR THE X-15

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FOREWORD

This is a report which describes the energy management concept which is employed in the Bell Aerosystems Company Energy Management System for the X-15. A description of the system in engineering equation form is given. A general description of the digital mechanization of this system on the SDS 930 and ALERT digital computers is given such that the equations in this report can be correlated with the computer programs that have been developed for these computers.

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I. INTRODUCTION

A. Background and Report Objectives

The Energy Management System that was originally developed by Bell Aerosystems Company for the X-15 was simply a version of the Bell Reentry Energy Management System (EMS) that was tailored for flight testing in the X-15. This work was done under a supplement to Contract AF33(657)-8330 and a report (ref. 1) on it was published in April 1963.

Since that time, Bell has been assisting the NASA Flight Research Center, under both NASA and Air Force contracts, in the research evaluation of this system. It was found early in this evaluation that, although the Bell Reentry EMS could be flight tested in the X-15, it was not particularly well suited to handle the type of energy management problems that are peculiar to the terminal flight phase in which the X-15 flies. As a result of this, the X-15 EMS was modified during this evaluation to adapt it to the energy management problems that arepeculiar to the X-15 and its flight regime. Although this modification did not change the basic Bell EMS concept, it did result in changes to nearly all parts of the EMS.

The majority of the changes that were made to the X-15 EMS simulation program for the SDS 930 computer and to the X-15 EMS flight test program for the ALERT computer were documented during this period (ref. 2). However, the documents on on these computer programs describe the X-15 EMS in computer languages for the associated computers. This makes it difficult for the reader of these documents to understand what changes have been made to the basic EMS equations presented in Ref. 1 unless he is familiar with these computer languages and with digital programming techniques.

Therefore, the basic object of this report is to describe the current form of the X-15 EMS in equation form. This includes all of the changes that have been made to it to date during the evaluation of it. In addition, it is also the object of this report to provide a general description of the mechanization of these equations in the SDS 930 and ALERT computer programs such that the reader can correlate between this report and the documents on these computer programs.

B. Report Content and Organization

Since the X-15 EMS has been designed to be mechanized on a digital computer, either ground based for simulation or airborne for flight testing, many of the equations and logic in it are associated with the digital nature of the system. Therefore, to enable the reader to better understand how the various EMS equations are phased and cycled through in a digital computer, a general description of the X-15 EMS and the digital computer mechanization of it has been included in Section II of this report. This description is in word form and, therefore, is applicable to both the SDS 930 and ALERT computer programs even though the languages for these two computers are different.

Section III of this report contains a description of the basic equations for the current form of the X-15 EMS. In general, these equations are presented in the same order and form in which they are mechanized in the two computer programs. However, where equations pertaining to different functions are intermingled in the computer programs, they have been separated in this report for clarity. In cases where the forms of the equations are different in the two computer programs, these differences are pointed out. In addition to the basic equations, the subroutine or section of each program where each group of equations is mechanized is given to enable the reader to correlate between this report and the documents on the computer programs.

To further enable the reader to correlate between this report and the documents on the computer programs, Section IV of this report contains a description ofthe symbology used in this report and the associated symbology which is used in the SDS 930 and ALERT computer programs. This section also contains a description of all the codes and discrete indicators which are used in the computer programs even though they have no corresponding engineering symbols.

II. GENERAL DESCRIPTION OF X-15 EMS AND ASSOCIATED COMPUTER PROGRAMS

A. General Description of X-15 EMS

The X-15 EMS is a guidance system which has been designed to be mechanized on an airborne digital computer for guiding the X-15 from the end of boost to the selected landing site. It does this by generating attitude and drag brake commands which, if followed, maneuver the X-15 to the selected landing site and dissipate or conserve energy as required to insure that the X-15 will arrive at the landing site area with the proper altitude and velocity for tying into the desired approach pattern for landing. These commands are also modulated and limited by the X-15 EMS to damp out phugoid flight path oscillations and to insure that none of the X-15's constraints are exceeded. The X-15 EMS has been designed such that these commands can be used in either a manual mode of operation, where they and other EMS information are displayed to the pilot, or in an automatic mode of operation, where they feed directly into the X-15's automatic flight control system.

The commands which are generated by the X-15 EMS are based on a predictive energy management system concept. The "heart" of this concept is a predictor which, in the X-15 EMS, is used to predict the maneuvering capability of the X-15 in the form of the ground area attainable (GAA) by the X-15 at each point in flight. From a guidance standpoint, the best position for the X-15 at each point in flight is one where its predicted ground area attainable (GAA) is centered about the selected landing site since this gives it the largest possible margin of safety in any direction. This point is referred to as the nominal point in the GAA. In the X-15 EMS, it is located somewhat ahead of the geometric center of the GAA because undesirable control action is required to keep the X-15's GAA geometrically centered about the selected landing site.

Once the GAA is predicted by the X-15 EMS, the nominal point in the GAA is located as a specific point on the earth's surface. The position of the selected landing site relative to this nominal point is then computed and used to generate commands to guide the X-15 to the landing site. These commands are generated in a manner which rapidly maneuvers the X-15 from its position at the end of boost to a position where the nominal point in its GAA coincides with the selected landing site. By doing this, the X-15 EMS insures that the X-15 will attain the selected landing site since, as the landing site is approached, the GAA shrinks to a point about the X-15 and, therefore, if the nominal point in this GAA and the selected landing site coincide, the X-15's position and the selected landing site must also coincide. In addition, this also insures that the X-15 will arrive at the selected landing site with the proper energy for tying into the desired approach pattern since the GAA is also predicted to this energy.

From the above description of the energy management concept that is employed in the X-15 EMS, it can be seen that this EMS accomplishes two basic functions: (1) it predicts the maneuvering capability of the X-15 to attain landing sites from each point in flight in the form of a ground area attainable (GAA), and (2) based on the position of the selected landing relative to the nominal point in this GAA, it generates commands to guide the X-15 to the selected landing site. In the X-15 EMS, the GAA is defined by predicting four boundary points of the X-15's maneuvering capability, maximum range, minimum range, and maximum left and right cross range, and by fitting a predetermined GAA boundary shape through these four points. The prediction of these four GAA boundary points is accomplished through the use of a flight predictor. The flight predictor is comprised mainly of a model of the X-15 in differential equation form. These equations are initialized in flight from sensed X-15 flight conditions and then integrated in fast time to predict all but the terminal position of each flight which determines a GAA boundary point. Since the time required to predict the terminal position of each flight by digital integration increases as the velocity decreases and since the maneuvering capability in this portion of flight is small compared to the total, this portion of each flight is predicted by closed form equations. The integrated and closed form portion of each flight is then added together to obtain the total predicted maneuvering capability.

Since the prediction of a complete GAA in this manner can take up to several seconds on a digital computer, a considerable time lag can result if predicted GAA is used directly to generate commands. To eliminate this lag, the X-15 EMS utilizes the predicted GAA's to set up coefficients for an extrapolator. The extrapolator is then used to extrapolate the predicted GAA to the current point in flight. The vehicle commands are then based on the position of the selected landing site in the extrapolated GAA.

The X-15 attitude and drag brake commands are generated by a command generation system in the X-15 EMS. In this system, the position of the selected landing site in the extrapolated GAA is first nondimensionalized. The nondimensional position of the selected landing site in the GAA is used to generate maneuver commands for guiding the X-15 to the landing site. These maneuver commands are then modulated and limited in a constraint control section to damp out flight path oscillations and to insure that none of the X-15's constraints are exceeded. The constrained maneuver commands are then transformed to the form required by the X-15 displays and automatic flight control system, if it is being used, and transmitted from the computer. This completes the operation of the EMS on a given cycle. The entire procedure just described is then repeated.

B. General Description of SDS 930 and ALERT Computer Programs for the X-15 EMS

During the research evaluation of the Bell X-15 EMS, the EMS has been programmed on both the SDS 930 computer and the ALERT airborne computer. The SDS 930 program was developed to simulate the operation of the EMS in real time. It operates in conjunction with the analog simulation of the X-15 at the NASA Flight Research Center. The ALERT computer program was developed for flight testing the EMS in the X-15. Although the languages that these programs are written in is different, the basic numerical computational procedures and logical decisions that are used in them are nearly identical. Therefore, only a single description of these programs is presented in this section and the differences between them are pointed out where they occur.

A general flow diagram of the digital programs, showing all of the major logical decisions and computational blocks, is presented in Figure 1. The normal route through the computational blocks is shown by the heavily shaded flow lines. From these, it can be seen that the programs normally obtain the EMS inputs first on any given cycle. In the SDS 930 program, these are obtained from the analog simulation of the X-15 and from the pilot selector switches in the X-15 simulation. In the ALERT computer, they are obtained from the navigational computations in the Verdan computer, vehicle sensors, and the pilot selector switches in the X-15 cockpit.

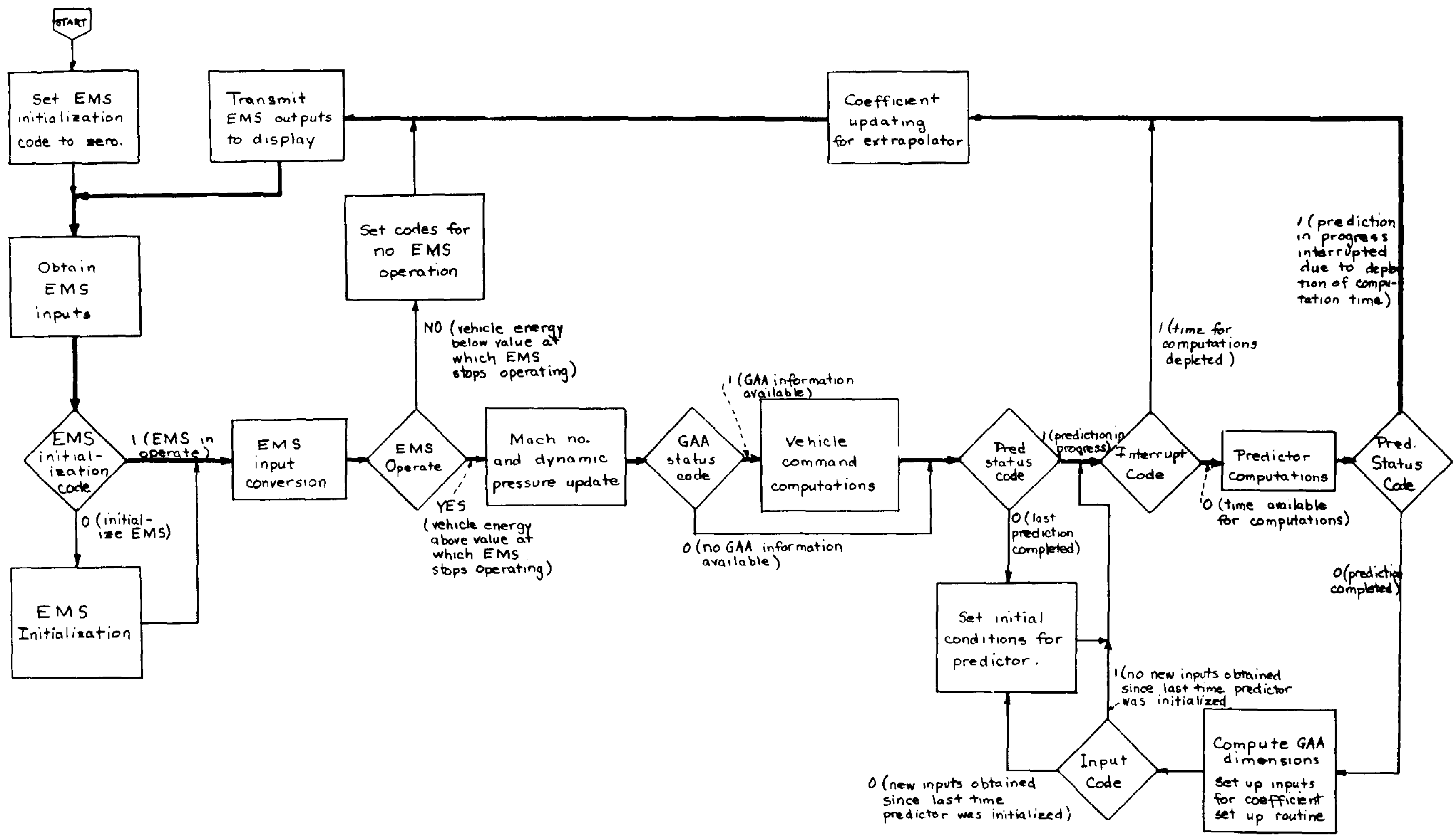

Figure 1.– Flow diagram of EMS digital programs.

In either case, these inputs are converted to the form required by the EMS and used to update the Mach number and dynamic pressure. A branch is then normally made to the vehicle command computations where the attitude and drag brake commands for the X-15 are generated. After these are completed, the programs branch to the predictor computations where the maneuvering capability of the X-15 is predicted in the form of a GAA. The prediction of the GAA is normally continued until it is time to generate commands for the X-15 again. At this time, an interrupt occurs which stops the predictor. A branch is then made to the coefficient updating computations where any of the GAA range predictions that have been completed during the current cycle are used to update the coefficients for the GAA range extrapolator. The current EMS outputs are then transmitted to the X-15 displays and the entire cycle is started over again.

Although the normal route through these programs is quite simple, it can be seen from Figure 1 that there are several secondary branches that can be made on any given cycle. These will now be explained. When the EMS first starts operating, certain parameters that are used in it must be initialized. To enable the EMS to determine when this occurs, an EMS initialization code is set to zero by the programs after the computers execute operation. This code is then tested by the programs after the EMS inputs have been obtained. If it is zero, the programs branch to an initialization section where the required parameters are initialized. The EMS initialization code is then set to one such that this initialization will be bypassed on subsequent cycles. The programs then return to the normal cycle route.

After the inputs are converted to the form required by the EMS, a test is made to determine if the X-15's energy has fallen below the terminal value at which the EMS stops operating. If the vehicle energy is greater than the terminal energy, the programs continue along the normal route. If it is less than the terminal value, the programs set an EMS status code to one to indicate that the EMS is stopping operation. This code is later used to set a signal which is transmitted to the cockpit displays. In addition, the programs set the EMS initialization code to zero to indicate that the EMS must be reinitialized if it starts operating again. The programs then branch to the section where the EMS outputs [1] are transmitted to the displays. The programs continue to cycle through this route as long as the vehicle energy is below the terminal value.

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(1) In this case the EMS status signal is the only meaningful output.

For the case where the normal route is taken, a test is made on the GAA status code after the Mach number and dynamic pressure have been updated. This code is set to zero when the EMS is initialized and remains zero until the first GAA has been predicted and used to set up coefficients for the GAA range extrapolator; at which point it is set to one. If it is one, the programs take the normal route through the vehicle command computations where the position of the selected landing site in the GAA is used to generate the vehicle maneuver commands. If it is zero, the programs bypass the vehicle command computations and branch directly to the predictor computations where the prediction of the GAA is either started, if the EMS has just been initialized, or continued.

Regardless of whether the normal route or bypass route is taken by the programs, the predictor status code is checked before the predictor computations are entered. This code is set to zero when the EMS is initialized. It is then either set to one by the predictor, if the prediction of any of the GAA ranges is interrupted before it is completed, or reset to zero by the predictor when the prediction of any of the GAA ranges is completed. Since the time required to predict the GAA is variable, the predictor is normally in the middle of a prediction when an interrupt occurs indicating that it is time to generate commands for the vehicle again. In this case, the predictor status code is one and the normal route is taken where the programs branch directly back into the predictor to continue the prediction that was interrupted. However, if the EMS has just been initialized or if the predictor has been interrupted at the completion of a prediction, the predictor status code is zero. In this case, the programs branch to a section where the predictor is initialized for a new prediction before the predictor is entered.

After the predictor computations are left, either due to being interrupted or completed, the predictor status code is again checked. If it is one, as it normally is due to an interrupt, the programs take the normal route which leads back to the vehicle command computations. However, if it is zero, as it will be if the prediction of any of the GAA ranges is completed between updates of the vehicle commands, the programs branch to a prediction processing and phasing section. In this section, the GAA dimension corresponding to the completed prediction is computed from the final results of it and the inputs to the coefficient set up subroutine are set up and saved for this prediction. The predictor control codes are then set for the next prediction.

Before the predictor is reentered, the input code is checked to determine if new inputs have been obtained by the EMS since the last time the predictor was initialized. This code is zero if they have and one if they have not. If it is zero, the predictor is initialized with these new inputs before it is reentered to start the next prediction. If it is one, the predictor initialization section is bypassed and the last set of predictor initial conditions are used. In either case, the interrupt code is also checked before the predictor is reentered to determine if computational time in the current cycle is available to start the next prediction. If it is zero, time is available and the predictor is re-entered. If it is one, as it will be when an interrupt occurs, the programs branch to the coefficient set up computations in the normal route. This in turn leads to a new updating of the vehicle commands.

III. DESCRIPTION OF X-15 EMS EQUATIONS

This section describes, in detail, the equations in each of the computational blocks shown previously in Fig. 1. In general, the equations in these blocks are discussed in the same order in which they appear in Fig. 1.

A. EMS Initialization (Part of subroutine EMCX in SDS 930 program; section PROGINIT in ALERT program)

When the EMS first starts operating, all of time dependent functions in the EMS which require previous history must be initialized since no previous history is available. In addition, all of the codes which control the cycling and phasing of the various computational blocks must be initialized. This initialization is discussed here because it is the first computational block that is entered by the programs when the EMS first starts to operate. However, since the reasons why the parameters and codes in this section are initialized the way they are cannot be fully described until the equations that they pertain to are discussed, it is suggested that the reader not dwell on this section, but instead, refer back to it as required while reading the subsequent sections.

The parameters which are initialized in this section are as follows:

$$t^{v}_{prev} = t^{v}$$

$$\alpha^{v}_{c\ prev} = \alpha^{v}$$

$$\phi^{v}_{B\ prev} = 0$$

$$\delta^{*}_{DB\ DZ} = 0$$

$$\Delta T^{v}_{off} = 0$$

$$\Delta I^{v}_{on} = 0$$

$$\Delta I^{P}_{off} = 0$$

$$(\partial R_{max}/\partial I)_{prev} = 0$$

$$(\partial R_{min}/\partial I)_{prev} = 0$$

$$(\partial R_{c\ max}/\partial I)_{prev} = 0$$

In addition, the following codes are set.

The EMS initialization code is set to a non zero value to indicate that the EMS has been initialized.

The vehicle status code is set to zero to indicate that it has not been determined if the X-15 has been dropped from the B-52.

The GAA status code is set to zero to indicate that no GAA is available for generating commands.

The vehicle time code is set to zero to indicate that the time dependent filters are to be initialized on this cycle.

The vehicle previous history code is set to zero to indicate that no previous history is available to generate commands.

The predictor status code is set to zero to indicate that the first prediction is to be started on this cycle.

The prediction type code is set to minus one to indicate that the first prediction is to be a maximum range prediction.

The predictor stopping code is set to one to indicate that the prediction is to be stopped when the stopping energy is reached.

The prediction phasing code is set to three to indicate that the processing computations for a maximum range prediction are to be entered after the first prediction is completed.

The prediction ready codes are set to zero to indicate that no predictions are available for setting up coefficients for the GAA range extrapolator.

The coefficient counter is set to six to indicate that six predictions (two of each kind; maximum range, minimum range, and maximum cross range) must be made before the coefficients for the GAA range extrapolator are completely set up.

The coefficient set up reset codes are set to zero to indicate that the coefficient set up process is just being started.

The previous value of the terminal energy indicator is set to the current value to indicate that it cannot be determined on the first cycle if the pilot has changed the selected terminal energy.

B. EMS Input Conversion and Updating (Part of subroutine EMCX in SDS 930 program; section CONVINPT in ALERT program)

The EMS input conversion and updating computations are comprised of the EMS input conversion computations and the Mach number and dynamic pressure updating computations shown previously in Fig. 1. In the EMS input conversion computations, the inputs obtained from the X-15 analog simulation in the SDS 930 simulator program or from the Verdan inertial computations and vehicle sensors in the ALERT airborne program, are transformed into the format required by the EMS. In the Mach number and dynamic pressure updating computations, the Mach number is computed and the dynamic pressure and density are either computed or obtained from sensed impact pressure depending on the accuracy of the sensed pressure.

1. EMS Input Conversion

In the SDS 930 simulation program, the coordinates of the X-15's position and the components of the X-15's velocity in the horizontal plane are obtained from the X-15 analog simulation in a range north coordinate system. The position coordinates are obtained as distances along the earth's surface from the Edwards reference. In the ALERT airborne program, these inputs are obtained from the inertial computations on the Verdan computer in a true north coordinate system and the X-15 position coordinates are in the form of increments in latitude and longitude from the Edwards reference. To obtain compatibility between the two programs, the SDS 930 program first transforms these inputs to a true north coordinate system and then transforms the X-15 position coordinates relative to true north into increments in latitude and longitude. The equations for transforming these inputs to true north are:

$$X^V = X^A \cos \Delta\xi^A - Y^A \sin \Delta\xi^A$$

$$Y^V = X^A \sin \Delta\xi^A + Y^A \cos \Delta\xi^A$$

$$\dot{X}^V = \dot{X}^A \cos \Delta\xi^A - \dot{Y}^A \sin \Delta\xi^A$$

$$\dot{Y}^V = \dot{X}^A \sin \Delta\xi^A + \dot{Y}^A \cos \Delta\xi^A$$

where $\Delta\xi^A$ is the heading angle between the two coordinate systems. The equations for transforming the above position coordinates to angular coordinates are:

$$\Delta\mu^V = X^V/r_e$$

$$\Delta\lambda^V = Y^V/(r_e \sin \lambda_o)$$

In the ALERT airborne program, the latitude and longitude increments and the horizontal plane velocity components are simply set equal to the values obtained from the Verdan computer.

$$\Delta\mu^V = \Delta\mu^I$$

$$\Delta\lambda^V = \Delta\lambda^I$$

$$\dot{X}^V = \dot{X}^I$$

$$\dot{Y}^V = \dot{Y}^I$$

In both programs, the true latitude and longitude of the X-15 are computed as

$$\mu^V = \mu_o + \Delta\mu^V$$

$$\lambda^V = \lambda_o \quad \Delta\lambda^V$$

The X-15 altitude and altitude rate are set equal to the values obtained from the X-15 analog simulation in the SDS-930 program and to the values obtained from the Verdan inertial computations in the ALERT program.

$$h^V = h^{A \text{ or } I}$$

$$\dot{h}^V = \dot{h}^{A \text{ or } I}$$

In both programs, the total velocity, heading, and flight path angle of the X-15 are computed as

$$(V_H^V)^2 = (\dot{X}^V)^2 + (\dot{Y}_V)^2$$

$$V^V = \sqrt{(V_H^V)^2 + (\dot{h}^V)^2}$$

$$V_H^V = \sqrt{(V_H^V)^2}$$

$$\sin \xi^V = \dot{Y}^V / V_H^V$$

$$\cos \xi^V = \dot{X}^V / V_H^V$$

$$\gamma^V = \arctan (\dot{h}^V / V_H^V)$$

The X-15 angle of attack is set equal to the value obtained from the X-15 analog simulation in the SDS-930 program and to the value sensed from the "Q ball" in the ALERT program. In both cases, the sine and cosine of it are computed.

$$\alpha^V = \alpha^{A \text{ or } S}$$

$$\sin \alpha^V = \sin (\alpha^V)$$

$$\cos \alpha^V = \cos (\alpha^V)$$

In the SDS 930 program, the dynamic pressure, q, is computed from the square root of q obtained from the X-15 analog simulation

$$q^{VS} = \left(\sqrt{q^{A}}\right)^{2}$$

In the ALERT program, the dynamic pressure is computed from the sensed impact pressure from the "Q ball."

$$q^{VS} = .53\ P_T^{\ S}$$

In the SDS 930 program, the normal acceleration is set equal to that obtained from the X-15 analog simulation.

$$A_N^{VS} = A_N^{A}$$

In the ALERT program, the normal acceleration is set equal to that sensed by the "z" body axis accelerometer in the X-15.

$$A_N^{VS} = A_N^{S}$$

In both programs, the vehicle energy is computed as

$$\dot{E} = 2E_T/m = (V^V)^2 + 2\ g_o\ h^V ,$$

where E_T is the total kinetic and potential energy in ft lb.

The terminal energy and coordinates associated with the desired landing site are selected from a stored table of values.

$$E_{final} = E_{HK\ final}(i), \text{ if pilot has selected high key terminal energy}$$

$$= E_{LK\ final}(i), \text{ if pilot has selected low key terminal energy}$$

$$\mu^D = \mu^D(i)$$

$$\lambda^D = \lambda^D(i)$$

The index, i, in this case is the desired landing site code and its value is set from the values on the discrete sense lines that come from the lake bed selector buttons in the cockpit.

The energy that the EMS stops operating at is an energy that is 40% higher than the terminal energy.

$$E_{stop} = 1.4\ E_{final}$$

The EMS operation is stopped at this point because the EMS commands become increasingly noisy as the terminal energy is approached. This is because these commands are based on the nondimensional position of the landing site in the GAA and, as the terminal energy is approached, any error in this position results in an error in the nondimensional position which approaches infinity.

As mentioned previously, if the vehicle energy, E, is below this value, the EMS sends a signal to the cockpit indicating that it is not operating and then enters a loop where it reads the inputs, converts them, and checks to see if the vehicle energy has gone above the stopping energy. If it is above the stopping energy, the program continues through the Mach number and dynamic pressure updating section.

2. Mach Number and Dynamic Pressure Updating

The velocity of sound is computed as a function of altitude from stored equations. This is divided into the X-15 velocity to obtain the X-15 Mach number

$$V_s = f_1\ (h^V)$$

$$M^V = V^V/V_s$$

The dynamic pressure updating must be made whenever the dynamic pressure that is obtained from sensed impact pressure is not accurate enough to be used. This situation occurs when the X-15 is attached to the B-52 and under certain flight conditions. It is assumed that the X-15 is attached to the B-52 if all of the following tests are false: (1) engine firing code indicates X-15 engine is firing, (2) past engine firing code indicates X-15 engine has fired in the past, and (3) X-15 velocity is greater than 1000 ft/sec. If any of these tests are true, the program assumes that the X-15 has been dropped from the B-52. In this case, it is assumed that the dynamic pressure obtained from sensed impact pressure is accurate enough to be used if all of the following flight condition tests are true;

(1) $M^V \geq M_{q\ lim}$, (2) $h^V \leq h_{q\ lim}$, and (3) $q^{VS} \geq q\ lim$.

In this case, the dynamic pressure is set equal to the value obtained from sensed impact pressure and the atmospheric density is computed from it and the vehicle velocity.

$$q^V = q^{VS}$$

$$\rho^V = 2\ q^V/(V^V)^2$$

If the X-15 is attached to the B-52 or if any of the flight condition tests stated previously are false, the atmospheric density and dynamic pressure are computed as follows

$$h_\rho^V = h^V \quad , \text{ if } h^V < h_{top}$$

$$= h_{top}, \text{ if } h^V \geq h_{top},$$

where: h_{top} = altitude at top of appreciable atmosphere

$$\rho^V = .0000253e^{-\beta_\rho (h_\rho^V - 105000)}$$

where: $$\beta_\rho = 4.32 \times 10^{-5} + 1.8 \times 10^{-10} h_\rho^V - 1.313 \times 10^{-15} (h_\rho^V)^2,$$

$$\text{if } h_\rho^V < 105{,}000$$

$$= 5.72 \times 10^{-5} - .915 \times 10^{-10} h_\rho^V \quad ,$$

$$\text{if } h_\rho^V \geq 105{,}000$$

$$q^V = .5 \rho^V (V^V)^2$$

At this point in the programs, all of the computations necessary to obtain the inputs in the form required by the EMS have been made. As mentioned previously, if GAA information is available at this point (see Figure 1) the program then computes the vehicle commands.

C. Vehicle Command Computations

The vehicle command computations are comprised of a GAA extrapolator section, a range computation section, a GAA nondimensionalization section, a maneuver command section, and a constraint section. In the GAA extrapolator section, the predicted GAA's are extrapolated to obtain the best current estimate of the range potentials of the vehicle. The actual range and cross range to the desired landing site are computed in the range computation section. These ranges and the vehicle's range potentials are then used to compute the nondimensional position of the landing site in the GAA. In the GAA maneuver command section, the vehicle commands for maneuvering to the desired landing site are computed from the nondimensional position of the landing site in the GAA. These commands are then limited and modulated in the constraint section as required to damp out flight path phugoid oscillations and to prevent the vehicle dynamic pressure and normal acceleration constraints from being exceeded.

1. GAA Extrapolator (Part of subroutine EMCX for SDS 930, part of OUTPTGEN for ALERT)

Since the prediction of a GAA takes a considerable amount of time (up to 2 sec on the ALERT computer and up to 6 sec on the SDS 930 computer), there would be a considerable lag in the vehicle commands if the predicted GAA's were used directly in computing them. To prevent this, the predicted GAA's are used to set up coefficients for an extrapolator and the extrapolator is then used to obtain the best estimate of GAA at the current point in flight using a straight line or linear extrapolation.

The independent variable that is used in the extrapolator is time when the X-15 engine is not firing and a combination of energy plus time when the X-15 engine is firing. To prevent a discrete change in the independent variable when the X-15 engine starts or stops firing, the difference between the two computations of it are tracked and then added on as a bias when the computation of it changes. The equations for this are as follows.

$$\Delta I^{v}_{off} = E^{v} - \Delta I^{v}_{on} \quad \text{, if engine firing code indicates engine not firing}$$

$$\Delta I^{v}_{on} = E^{v} - \Delta I^{v}_{off} \quad \text{, if engine firing code indicates engine firing}$$

$$\Delta I^{v} = E^{v} - \Delta I^{v}_{off} + k_t \, t^{v}$$

The current range potentials of the vehicle in terms of the maximum and minimum range and maximum cross range coordinates of the GAA are extrapolated as follows,

$$R_{max} = R_{max\ 0} + (\partial R_{max}/\partial I)\ I^{v}$$

$$R_{min} = R_{min\ 0} + (\partial R_{min}/\partial I)\ I^{v}$$

$$R_{c\ max} = R_{c\ max\ 0} + (\partial R_{c\ max}/\partial I)\ I^{v}$$

where $R_{max\ 0}$, etc. and $(\partial R_{max}/\partial I)$, etc. are the coefficients that are set up from the GAA predictions.

2. Range Computations (Part of subroutine EMCX for SDS-930; part of OUTPTGEN for ALERT)

The actual range and cross-range from the vehicle to the landing site are computed from the latitude and longitude coordinates of the vehicle and landing site and from the heading of the vehicle as follows.

$$\Delta\mu^D = \mu^D - \mu^v$$

$$\Delta\lambda^D = \lambda^D - \lambda^v$$

$$R_{TG} = K_{nm/rad}[\Delta\mu^D \sin\lambda_o \cos\xi^v + \Delta\lambda^D \sin\xi^v]$$

$$R_c = K_{nm/rad}[-\Delta\mu^D \sin\lambda_o \sin\xi^v + \Delta\lambda^D \cos\xi^v]$$

The straight line distance from the X-15 to the landing site is computed as,

$$R = \sqrt{R_{TG}^2 + R_c^2}$$

3. GAA Nondimensionalization (Part of subroutine EMCX for SDS 930, part of OUTPTGEN for ALERT)

The position of the landing site in the GAA is nondimensionalized by transforming the GAA into a circle of unit radius as shown in Figure 2. In this coordinate system, the nondimensional range position of the landing site is determined by dividing the difference between range to the landing site and the nominal range by one half the GAA length. In a like manner, the nondimensional cross-range position of the landing site is determined by dividing the cross-range to the landing site (the nominal is defined as zero in this case) by one half the width of the GAA or the maximum cross-range. From this, it can be seen that the nondimensionalized coordinates of the landing site are 0, 0 when it is in the center of the GAA. The equations for this are as follows,

$$R_{nom} = (R_{max} + R_{min})/2$$

$$\Delta R^* = \frac{R_{TG} - R_{nom}}{R_{max} - R_{nom}}$$

$$R_c^* = R_c / R_{c\ max}$$

In addition, a nondimensional maneuver command range error signal, which is used later to generate the maneuver commands required to guide the vehicle to the selected landing site, is generated by adding a bias to the geometric nondimensional range error, ΔR^*, at zero R_c^* and a slope term which sweeps the maneuver command range error aft as R_c^* increases,

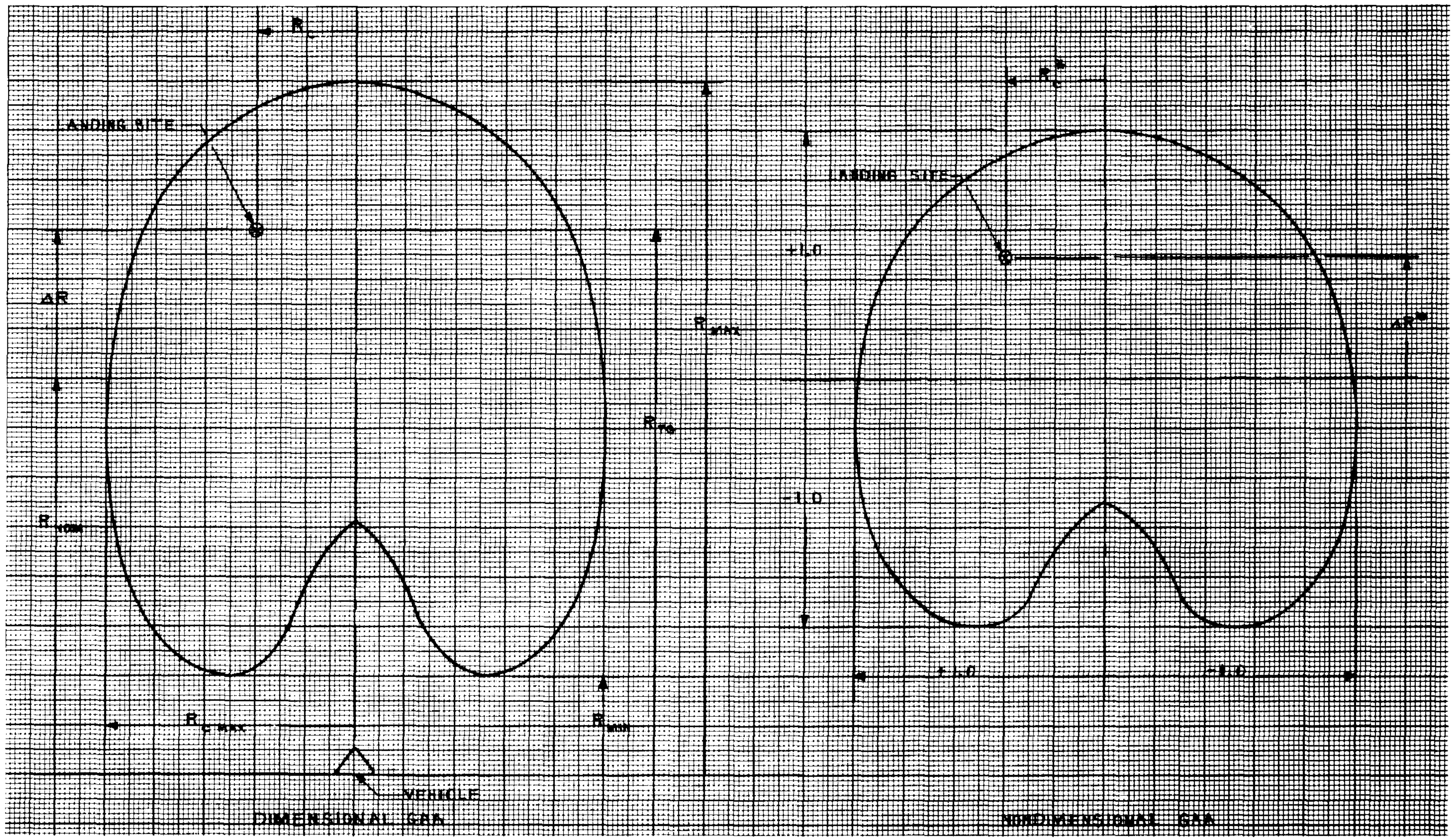

Figure 2.— GAA coordinate system and nondimensionalization.

$$\Delta R_B^* = \Delta R^* + b_{\Delta R^*} - m_{\Delta R^*/R_c} * (|R_c^*\ R_c^{*1}|),$$

where: $R_c^{*1} = 1 - \Delta R^{*1}\ (1 - |R_c^*|)$

$$\Delta R^{*1} = 1 + \Delta R_{B\ prev}^* \ ; \ 0 \leq \Delta R^{*1} \leq 1.0$$

A nondimensional radial error signal, which is also used later to generate the maneuver commands required to guide the vehicle to the desired landing site, is computed as,

$$\Delta \bar{R}^* = \sqrt{(\Delta R_B^* - b_{\Delta R^*} + .075)^2 + (R_c^*)^2}$$

All of these nondimensional terms are passed through a first order filter of the form, 1/(T s + 1), before being used to generate the maneuver commands. This prevents noise in these terms, which can be caused by noise in the EMS inputs and by errors in the EMS computations themselves, from feeding directly into the maneuver commands. This filter is mechanized as a discrete difference equation in the computer program as follows,

$$\Delta R_f^* = (\Delta R^*\ \Delta t^V + \Delta R^*_{prev}\ T) \ / \ (T + \Delta t^V)$$

$$R_{cf}^* = (R_c^*\ \Delta t^V + R^*_{c\ prev}\ T) \ / \ (T + \Delta t^V)$$

$$\Delta R_{Bf}^* = (\Delta R_B^*\ s\ \Delta t^V + R^*_{B\ prev}\ T) \ / \ (T + \Delta t^V)$$

$$\Delta \bar{R}_f^* = (\bar{R}^*\ \Delta t^V + \Delta \bar{R}^*_{prev}\ T) \ / \ (T + \Delta t^V)$$

The time constant, T, in these filters is set as follows

$T = 0$, if pilot has changed landing site selection

$T = 1$, if landing site selection has not changed and engine is firing.

$T = 3$, if landing site selection has not changed and engine is not firing.

4. Maneuver Command Generation

In this section, the angle of attack, bank angle, and drag brake commands for maneuvering the X-15 to the selected landing site are computed as functions of the position of the landing site in the nondimensional GAA. In all cases, the commands are generated to rapidly maneuver the X-15 from its initial position to a position where the landing site is centered at a nominal point in the X-15's GAA and then to maneuver the X-15 such that the landing site remains centered at this nominal point. This control philosophy insures that: (1) the X-15 will be rapidly maneuvered to a point where it can correct for the largest possible errors in any direction from the nominal point that might occur later in flight due to such things as unexpected winds and/or errors in the navigational computations of position and velocity and (2) that the X-15 will reach the desired landing site at the desired terminal energy since the X-15's GAA shrinks to zero about the X-15 as the terminal energy is approached and, therefore, if the landing site is kept at the nominal point inside the GAA, the X-15 and landing site positions will approach each other as this energy is approached. The shape of these commands and the equations which are used for generating them in the programs are discussed in the following sections.

a. Angle of Attack Commands (Part of subroutine COMX in SDS-930 program, part of subroutine COMDGEN in ALERT program)

The angle of attack maneuver command which is generated in this section is shown in Figure 3 as a function of the position of the landing site in the nondimensional GAA. From this figure, it can be seen that the angle of attack command is for maximum L/D whenever the landing site is in the front end of the GAA and requires range stretching to attain. When the landing site is in the heart-shaped region, which is centered aft of the GAA center, and requires range shortening to attain, the command is for minimum angle of attack on the front side of the L/D curve. When the landing site is in the extreme aft end of the GAA and requires an "S" turn maneuver to attain or in the aft corners of the GAA and requires a "U" turn maneuver to attain, the command is for maximum angle of attack on the back side of the L/D curve since additional lift is required for laterally turning in these cases. Between these regions, the command is varied linearly between the respective values for each region.

In generating these commands, the maximum angle of attack and angle of attack for maximum L/D are first computed in the programs as,

$$\alpha_{max} = f_2(M^V, \delta^{*}_{DB}{}^{V}_{rl}, k^V \delta H)$$

where: M^V = vehicle Mach number

$\delta^{*v(1)}_{DB\ rl}$ = rate limited deflection of vehicle drag brakes

$k^{v(1)}_{\delta H}$ = fraction of allowable deflection of X-15's horizontal stabilizers

$$\alpha_{(L/D)max} = f_3(M^V)$$

Footnote. (1) See Section C.5.a. (3) for description of these parameters.

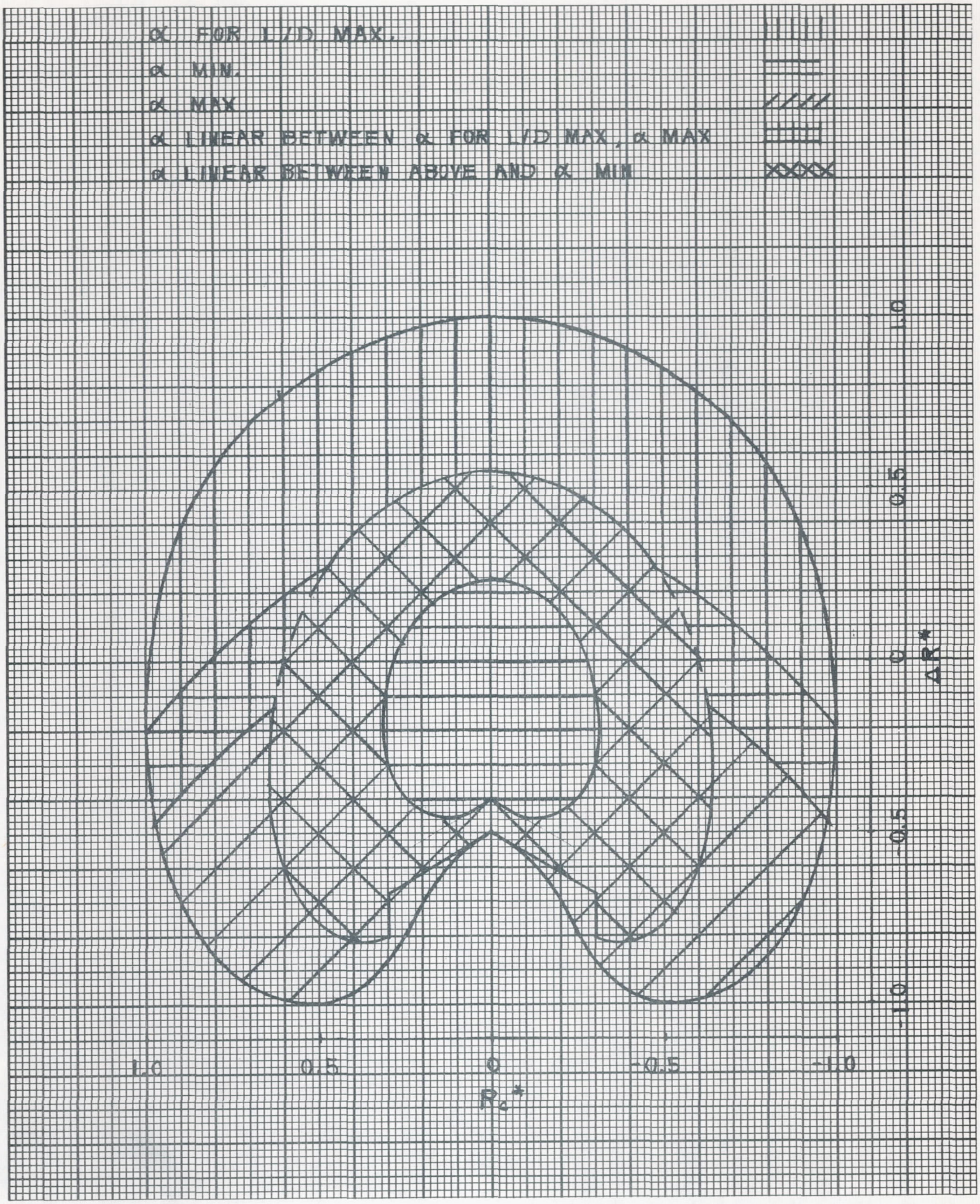

Figure 3.— Angle of attack maneuver commands.

The angle of attack command on the back side of the L/D curve is then computed as,

$$\alpha_{BS} = \alpha_{(L/D)max} - 3.33\ \Delta R^{*}_{Bf}\ (\alpha_{max} - \alpha_{(L/D)max})$$

$$\alpha_{BS\ 1} = \alpha_{BS} \text{ limited to: } \alpha_{(L/D)max} \leq \alpha_{BS} \leq \alpha_{max}$$

If the landing site is outside the outer boundary of the heart-shaped region shown in Figure 3, the angle of attack command is set equal to the angle of attack command on the back side of the L/D curve.

$$\text{If} \quad \Delta\bar{R}^{*}_{f} > b_{\Delta R^{*}},\ \alpha_{mc} = \alpha_{BS\ 1}$$

If the landing site is inside the outer boundary of the heart-shaped region, the angle of attack command on the front side of the L/D curve is computed.

$$\text{If} \quad \Delta\bar{R}^{*}_{f} \leq b_{\Delta R^{*}}$$

$$\Delta\alpha_{FS} = k_{\Delta R^{*}}\ (b_{\Delta R^{*}} - \Delta\bar{R}^{*})(\alpha_{BS\ 1} - \alpha_{min})$$

$$\Delta\alpha_{FS} \text{ is limited: } 0 \leq \alpha_{FS} < \alpha_{BS\ 1} - \alpha_{min}$$

$$\alpha_{mc} = \alpha_{BS\ 1} - \Delta\alpha_{FS}$$

The outer boundary limit, $b_{\Delta\bar{R}*}$, of the heart-shaped region and the gain, $k_{\Delta\bar{R}*}$, each have two discrete values which are set during the generation of the bank angle maneuver commands which will be discussed next.

b. Bank Angle Commands (Part of subroutine COMX in SDS 930 program, part of subroutine COMDGEN in ALERT program)

The bank angle maneuver command which is generated in this section is shown in Figure 4 as a function of the position of the landing site in the nondimensional GAA. From this figure it can be seen that, except near the boundary of the GAA, the bank angle command is directly proportional to the nondimensional cross range error, R_c^* , where the constant of proportionality increases as the landing site moves aft in the GAA. However, as the boundary of the GAA is approached, the commands become limited, except in the bank reversal zone, by limits that spiral radially outward from the GAA nominal point. These limits prevent the vehicle from dissipating too much energy during the turn. This is necessary in this case since, when making large lateral turns, energy is required for range stretching after the turn is made.

When the landing site is in the bank reversal zone, a "S" turn maneuver is used to attain it. In this case, banking is required even if no cross-range error exists. Since the "tightness" of the "S" turn increases rapidly as the landing site moves aft in this region, the bank command also increases rapidly as the site moves aft.

In generating these commands, the bank angle command for correcting for cross-range errors when the landing site is outside of the bank reversal zone is computed as,

$$|\phi_{mc/R_c^*}| = k_{\phi/R_c^*} \left(1 - k_{R_c^*/\Delta R^*}\right) | R_c^* |,$$

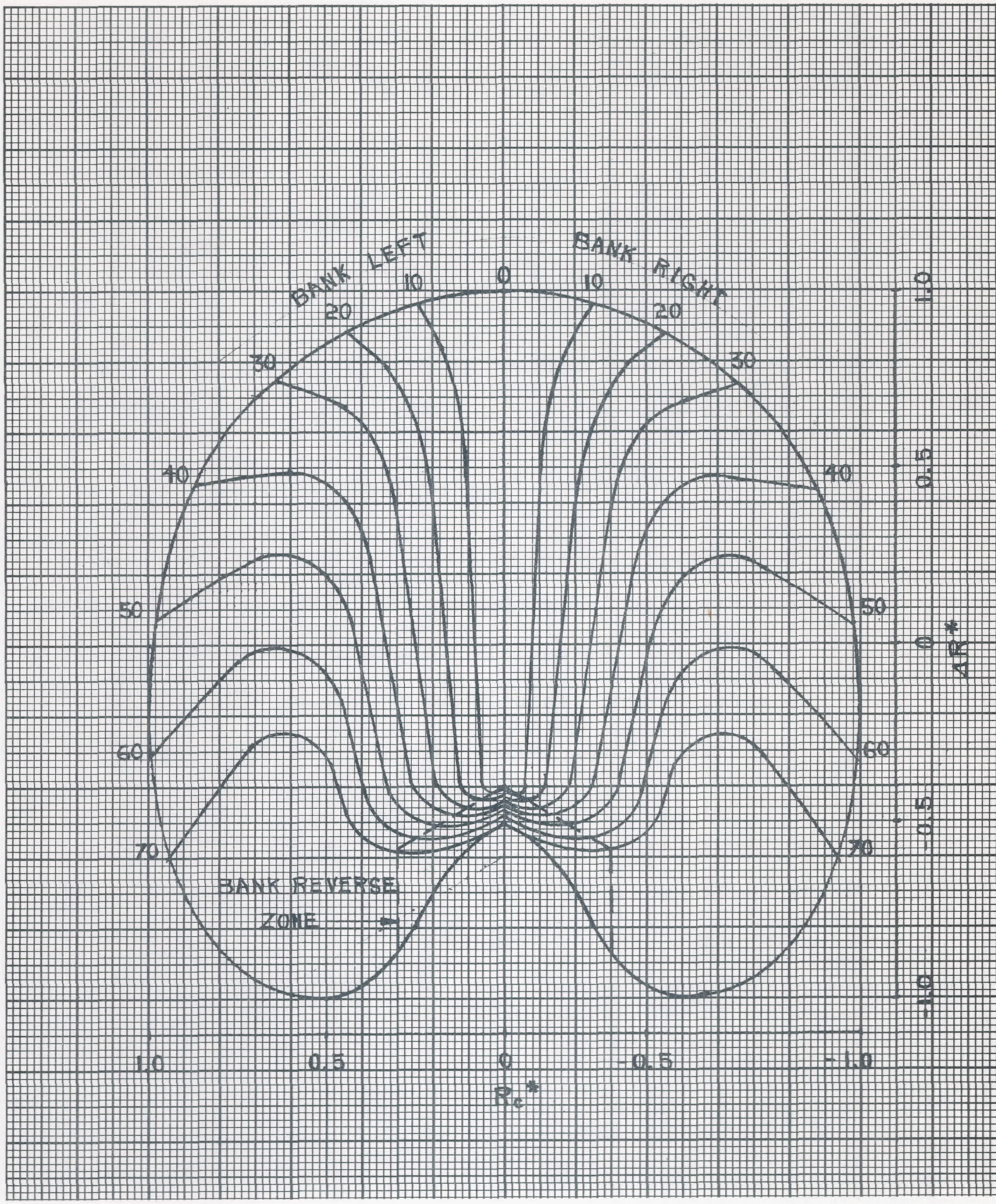

Figure 4.— Bank angle maneuver commands.

where: $k_{R_c^*/\Delta R^*} = \Delta R_B^*$, if $\Delta R_B^* < 0$

$= 0$, if $\Delta R_B^* \geq 0$

If the landing site is fore of the front boundary of the bank reversal zone shown in Figure 4, the bank angle maneuver command is set equal to this command.

$$\text{If} \quad \Delta R_B^* \geq \Delta R_{Blim}^* , \; |\phi_{mc}| = |\phi_{mc/Rc^*}|$$

If the landing site is aft of the front boundary of the bank reversal zone, an increment in bank angle for the "S" turn is computed and added to that for correcting the cross-range error.

$$\text{If} \quad \Delta R_B^* < \Delta R_{B\,lim}^*$$

$$|\Delta\phi_{\Delta R^*}| = - k_{\phi/\Delta R^*} (\Delta R_B^* + \Delta R_{Blim}^*)$$

$$|\phi_{mc}| = |\phi_{mc/R_c^*}| + |\phi_{mc/\Delta R^*}|$$

At this point in the programs, the magnitude of the bank angle maneuver command has been computed. The signing of the command is determined from the location of the landing site in the GAA. The command has the sign of R_c^* whenever the landing site is outside the bank reversal zone and the opposite sign of

R_c^* whenever the landing site is inside the bank reversal zone with one exception; when the range, R_{TG}, to the landing site becomes negative. Due to a reversal in the sign of the bank angle required to correct a cross-range error in this case, the bank command has the sign of R_c^*.

Since the gain, $k_{\Delta \bar{R}^*}$, and the outer boundary limit, $b_{\Delta \bar{R}^*}$, which are used in generating the angle of attack maneuver command, are also dependent on the same conditions that determine the sign of the bank command, they are also set in this section of the program. The logic for this is as follows.

$$\phi_{mc} = |\phi_{mc}| \text{ sgn } (R_c^*)$$

$$k_{\Delta R^*} = 10.$$

$$b_{\Delta R^*} = .43 \qquad\qquad , \text{ if } R_{TG} - \Delta R_{TG/DZ} < 0$$

$$\phi_{mc} = |\phi_{mc}| \text{ sgn } (R_c^*)$$

$$k_{\Delta R^*} = 3.3$$

$b_{\Delta R^*} = .63$, if $(R_{TG} - \Delta R_{TG/DZ} > 0)$

and $[(\Delta R_B^* \geq \Delta R_{B\ lim}^*)$ or

$(\Delta R_B^* < \Delta R_{B\ lim}^*$ and $|R_c^*|$

$> R_{c\ lim}^*)]$; outside bank reversal zone

$$\phi_{mc} = - |\phi_{mc}| \operatorname{sgn} (R_c^*)$$

$$k_{\Delta R^*} = 10.$$

$b_{\Delta R^*} = .43$, if $(R_{TG} - \Delta R_{TG/DZ} > 0)$

and $(\Delta R_B^* < \Delta R_{B\ lim}^*$ and

$|R_c^*| \leq R_{c\ lim}^*)$; inside bank reversal zone

In this logic, the term $R_{TG/DZ}$, is a dead zone increment which is added to the range to prevent the sign of the bank command from chattering when the range is near zero. The term, $\Delta R_{B\ lim}^*$, is the nondimensional control range coordinate of the front boundary of the bank reversal zone. The term, $R_{c\ lim}^*$, is the cross-range coordinate of the side boundary of the bank reversal zone and it also includes a dead zone to prevent the sign of the bank command from chattering. It is set as follows.

$$R^*_{c\ lim} = .25, \text{ if bank reversal indicator} = 0$$
$$= .30, \text{ if bank reversal indicator} \neq 0$$

The bank reversal indicator and the range dead zone increment are set as follows.[1]

Bank reversal indicator = 1

$$\Delta R_{TG/DZ} = -1.0 \qquad , \text{ if } \phi_{mc}\, R^*_c > 0;$$
outside bank reversal zone

Bank reversal indicator = 0

$$\Delta R_{TG/DZ} = 0 \qquad , \text{ if } \phi_{mc}\, R^*_c \leq 0;$$
inside bank reversal zone

At this point, the equations and logic for computing the magnitude and sign of the bank angle command have been given. The limit, which limits the bank angle maneuver commands as the landing site approaches the GAA boundary is computed as,

$$\phi_{mc\ lim} = k_{\phi\ lim}\, \Theta_{GAA},$$

where Θ_{GAA} is the polar angle defined by,

$$\Theta_{GAA} = \tan^{-1} \left(|R^*_c| / \Delta R^*_B \right)$$

Since arctan subroutines are time consuming on digital

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(1) This logic is a part of subroutine EMCX in SDS-930 program; part of OUTPTGEN in ALERT program.

computers and since the polar angle, Θ_{GAA}, does not have to be very accurate, a fast approximation for the arctan functions is used in the programs. This approximation is as follows.

$$\Theta_{GAA} = 90, \text{ if } (\Delta R_B^* = 0) \text{ or } (\Delta R_B^* < 0 \text{ and } R_c^* = 0)$$

$$\Theta_{GAA} = 45 \tan \Theta_{GAA}, \text{ if } [(\Delta R_B^* > 0) \text{ or } (\Delta R_B^* < 0 \text{ and } R_c^* \neq 0)]$$
$$\text{and } (\tan \Theta_{GAA} \text{ is } + \text{ and } \tan \Theta_{GAA} < 1.0)$$

$$\Theta_{GAA} = 90 - 45 \tan \Theta_{GAA}, \text{ if } [(\Delta R_B^* > 0) \text{ or } (\Delta R_B^* < 0 \text{ and } R_c^* \neq 0)]$$
$$\text{and } [(\tan \Theta_{GAA} \text{ is } -) \text{ or } (\tan \Theta_{GAA} > 1)]$$

For all of these cases, the $\tan \Theta_{GAA}$ is computed as

$$\tan \Theta_{GAA} = |R_c^*| \,/\, \Delta R_B^*$$

The bank angle limit computed above is used to limit the bank angle maneuver command as follows.

ϕ_{mc} is limited to: $-\phi_{mc\ lim} \leq \phi_{mc} \leq \phi_{mc\ lim}$

c. Drag Brake Maneuver Command (Part of Subroutine EMCX in SDS 930 program, part of OUTPTGEN in ALERT program)

The drag brake maneuver command which is generated in this section is shown in Figure 5 as a function of the position of the landing site in the nondimensional GAA. As can be seen from this figure, no drag brake deflection is commanded when the landing site is more than a small increment fore of the GAA nominal point and requires range stretching to attain it. However, as the landing site moves aft of the GAA nominal point and requires range shortening to attain it, the drag brake command increases to maximum deflection; except near the GAA boundary. When the landing site is near the GAA boundary and requires a large lateral turn to attain, energy must be conserved for range stretching after the turn is made. In this case, the drag brake command is limited to prevent too much energy from being dissipated during the turn; as was done for the bank angle maneuver command in this case.

As can be seen from Figure 5, only one intermediate drag brake command exists between the no deflection and maximum deflection commands. This is because only three discrete indicators are available in the X-15 cockpit to display the EMS drag brake command to the pilot. The drag brake maneuver command is generated in this section as a continuous command. It is converted to a discrete command after it has passed through a continuous constraint section. Therefore, this conversion process will be discussed after the equations in the constraint section are discussed.

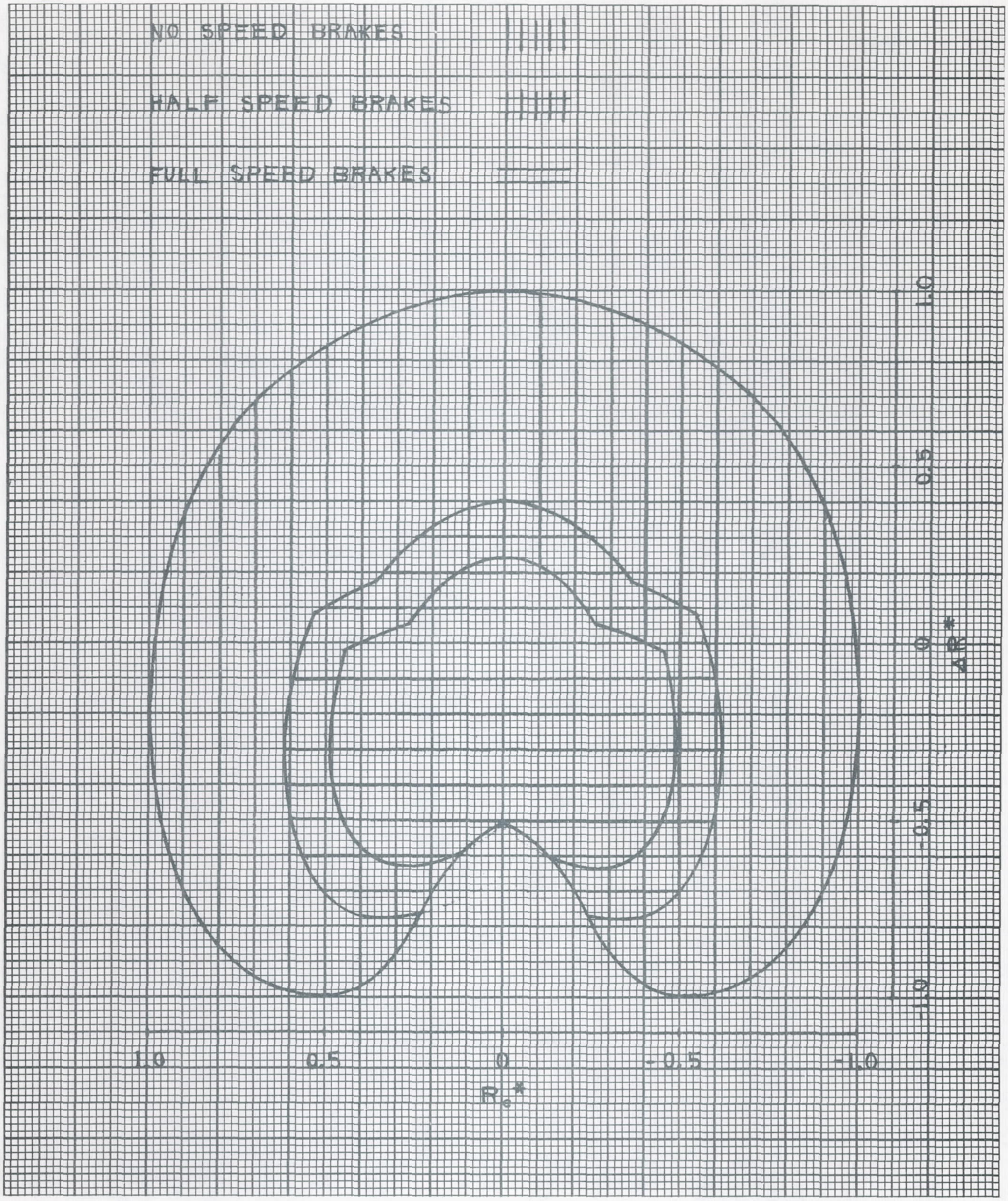

Figure 5.– Speed brake maneuver commands.

The drag brake maneuver command is computed as,

$$\delta v^*_{DB\ mc} = \mathrm{Max}\ (\delta v^*_{DB/\Delta\bar{R}^*}\ ,\ \delta v^*_{DB/\Delta R^*_B})\ ,$$

where:

$$\delta v^*_{DB/\Delta\bar{R}^*} = -3.33(\Delta\bar{R}^* - .5)$$

$$\delta v^*_{DB/\Delta R^*_B} = -\ 3.33\ \Delta R^*_B$$

The limit, which limits this command as the GAA boundary is approached, is computed as,

$$\delta v^*_{DB\ lim} = 5.0\ (0.7 - \Delta\bar{R}^*)$$

The maneuver command is them limited as follows.

$\delta v^*_{DB\ mc}$ is limited to: $\delta v^*_{DB\ mc} \leq \delta v^*_{DB\ lim}$

5. Constraint Control

The constraint control section of the programs contains control loops that modulate and limit the maneuver commands as required to damp out phugoid flight path oscillations and to insure that the vehicle constraints do not exceed critical values. Two constraint control loops are included: one for controlling the vehicle dynamic pressure and one for controlling the vehicle normal acceleration. In addition, the maneuver commands are limited such that they do not exceed the attitude limits on the X-15 such as the maximum trimmable angle of attack and the maximum allowable bank angle.

Since the constraints which are imposed on the vehicle maneuver commands in this section must also be imposed on the predictor maneuver commands if the predicted GAA is to be an accurate indication of what the vehicle can attain, a major portion of the constraint control loops in this section are mechanized as subroutines in the computer programs which are used in both the vehicle and predictor command computations. Therefore, this subroutine will be discussed in this section for both the vehicle and predictor to prevent duplication when the predictor computations are discussed. However, before this is done, the computation of certain vehicle constraints which are used in the constraint control loops will be discussed.

a. Damping and Constraint Computations

(1) Damping Parameter (Part of subroutine EMCX in SDS-930 program; part of OUTPTGEN in ALERT program)

A nondimensional damping parameter is used in the constraint control loops which damp out the vehicle phugoid flight path oscillations. This damping parameter is computed as,

$$\dot{H}^{*V} = 1.0 - \dot{h}^V/\dot{h}^V_{eq} \ ,$$

where $\dot{h}^V_{eq}$ is the equilibrium altitude rate. From this expression, it can be seen that the damping parameter is zero whenever the vehicle is falling at the equilibrium altitude rate, -1.0 if it is falling twice as fast as this rate, -2.0 if it is falling three times as fast as this rate, etc.

It can be analytically shown that the equilibrium altitude rate is given by,

$$\dot{h}^V_{eq} = \frac{2g}{(L/D)^V \cos \phi^V \ [\beta V^V + 2g/V^V]}$$

where β is the density decay parameter. Since the bank angle of the X-15 is not available as in input to the ALERT program and since the acceleration inputs which are available are not accurate enough to be used to obtain the L/D ratio in most cases, the term $(L/D)^V \cos\phi^V$, which is the vertical component of the X-15's L/D ratio is approximated by an average value in the computer programs. The equilibrium altitude rate equation thus becomes,

$$\dot{h}^{v}_{eq} = \frac{2g}{(L/D_{v\ avg}\ [\beta V^{v} + 2g/V^{v}]}$$

The error that results in the damping parameter from this approximation is not large enough to adversely affect the operation of the damping loops when the damping parameter is large and damping is really needed. To eliminate the steady state error that can exist when the damping parameter is small, this damping parameter is passed through a washout filter in the constraint control equations before being used in the damping control loops.

(2) Normal Acceleration (Part of Subroutine EMCX in SDS-930 program, part of subroutine COMNDGEN in ALERT program)

Although sensed normal acceleration is available directly from one of the X-15 accelerometers, it is not used directly in the normal acceleration control loop since studies have shown that the large short period fluctuations in it, that can be caused by such things as sudden control surface movements, can cause instabilities in the type of sampled data control loop used. Instead, the slope of the normal coefficient is factored from the sensed acceleration, limited to within reasonable bounds, and then used to compute a normal acceleration. This computed normal acceleration is equal to the sensed acceleration whenever the computed slope of the normal coefficient is within its reasonable bounds.

However, when the slope of the normal coefficient is outside reasonable bounds, the computed acceleration is that which results from limiting values of the slope of the normal coefficient. Although the limiting in this case filters out the large short period fluctuations, it does not affect the average short period value since this cannot be greater or less than that which results from the limiting values of the slope of the normal coefficient.

The equations for this are as follows:

$$C^{v}_{N\alpha} = - A^{vs}_{N}\ m/(q^{v}\ S\ \alpha^{v})$$

$C^{v}_{N\alpha}$ is limited to: $.0215 < C^{v}_{N\alpha} \leq .070$

$$- A^{v}_{N} = q^{v}\ (S/m)\ C^{v}_{N\alpha}\ \alpha^{v}$$

The number of "g's" of normal acceleration per unit angle of attack is computed as,

$$[(\partial A^{v}_{N}/\partial\alpha)/g_{o}] = - A^{v}_{N}/\alpha g_{o})$$

(3) Constraints on Maximum Trimmable Angle of Attack (Part of subroutine EMCX in SDS-930 program; part of OUTPTGEN in ALERT program)

The maximum angle of attack that the X-15 can trim is a function of the Mach number, the deflection of the X-15 drag brakes, and the horizontal stabilizer deflection. The drag brakes constrain the maximum trimmable angle of attack by an amount that is proportional to the deflection of the drag brakes. However, the only drag brake input available to the EMS is a discrete signal which indicates that the X-15 drag brakes are either deflected or not deflected. If this signal were used directly to constrain the maximum angle of attack that is computed in the EMS, the maximum angle of attack would make a step change every time the status of the drag brake indicator changed. To prevent this from happening, the drag brake deflection corresponding to the status of this indicator is passed through a rate limiter to obtain a signal which changes gradually when the status of the discrete drag brake indicator changes. This rate limited signal is then used to constrain the maximum angle of attack.

The equations for this are as follows.

$$\delta_{DB}^{*v} = 0. \quad \text{, if drag brake indicator is zero}$$

$$= 1.0 \text{ , if drag brake indicator is one}$$

$$\text{(full deflection assumed)}$$

$$\Delta\delta_{DB}^{*} = \dot{\delta}_{DB\ man}^{*} \ \Delta t^{v}$$

$$\delta^{*v}_{DB\ rl} = \delta^{*v}_{DB} \text{ limited to:}$$

$$\delta^{*v}_{DB\ prev} - \Delta\delta^{*}_{DB} \leq \delta^{*v}_{DB} \leq \delta^{*v}_{DB\ prev} + \Delta\delta^{*}_{DB}$$

$$\delta^{*v}_{DB\ prev} = \delta^{*v}_{DB\ rl}$$

The maximum trimmable angle of attack that is computed in the EMS is also constrained by the amount of full horizontal stabilizer deflection that the EMS is allowed to use. A button is available in the cockpit such that the pilot can select either maximum or 75% of maximum horizontal stabilizer deflection. However, even when the horizontal stabilizer indicator indicates that the pilot has selected full deflection, the EMS constrains the deflection to 75% of maximum except when maximum is needed. It is assumed that maximum is needed whenever the nondimensional damping parameter is less than -10, as would be the case on reentry from an altitude mission, or whenever the dynamic pressure approaches 1600 psf. The gain which is used to constrain the deflection is computed as,

$$k^{v}_{\delta H} = (q^{v}/1600) - .05\ \dot{H}^{*v}$$

As can be seen from this expression, this gain is one when maximum deflection is needed and zero or less when only 75% of maximum deflection is needed.

b. Damping and Constraint Control Loops

The damping and constraint control loops, which modulate and limit the vehicle maneuver commands as required to damp out phugiod flight path oscillations and to insure that the vehicle dynamic pressure and normal acceleration constraints do not exceed critical values, are shown in Figure 6 in functional form. As mentioned previously, a major portion of these control loops are mechanized as a subroutine which is also used in the computation of the predictor commands. This portion contains all of the control loops on that angle of attack and bank angle shown in Figure 6 except for the normal acceleration control loop. The control loops on the drag brake deflection command shown in this figure are not contained in this subroutine since they are required only for the vehicle. They are not required for the predictor since the predictor drag brake commands are always for no deflection.(1)

(1) Control Loops on Angle of Attack and Bank Angle (Part of subroutine CCMX in SDS 930 program; part of subroutine COMNDGEN in ALERT program)

Logic

In this section, a certain amount of logic is necessary to set the parameters required in the control loops

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(1) The predictor drag brake command is always for no deflection since studies have shown that they are not beneficial on flights to the GAA boundary points that the predictor predicts.

equal to those for the vehicle when it is being used for the vehicle and to those for the predictor when it is being used by the predictor. The parameters which must be set are as follows.

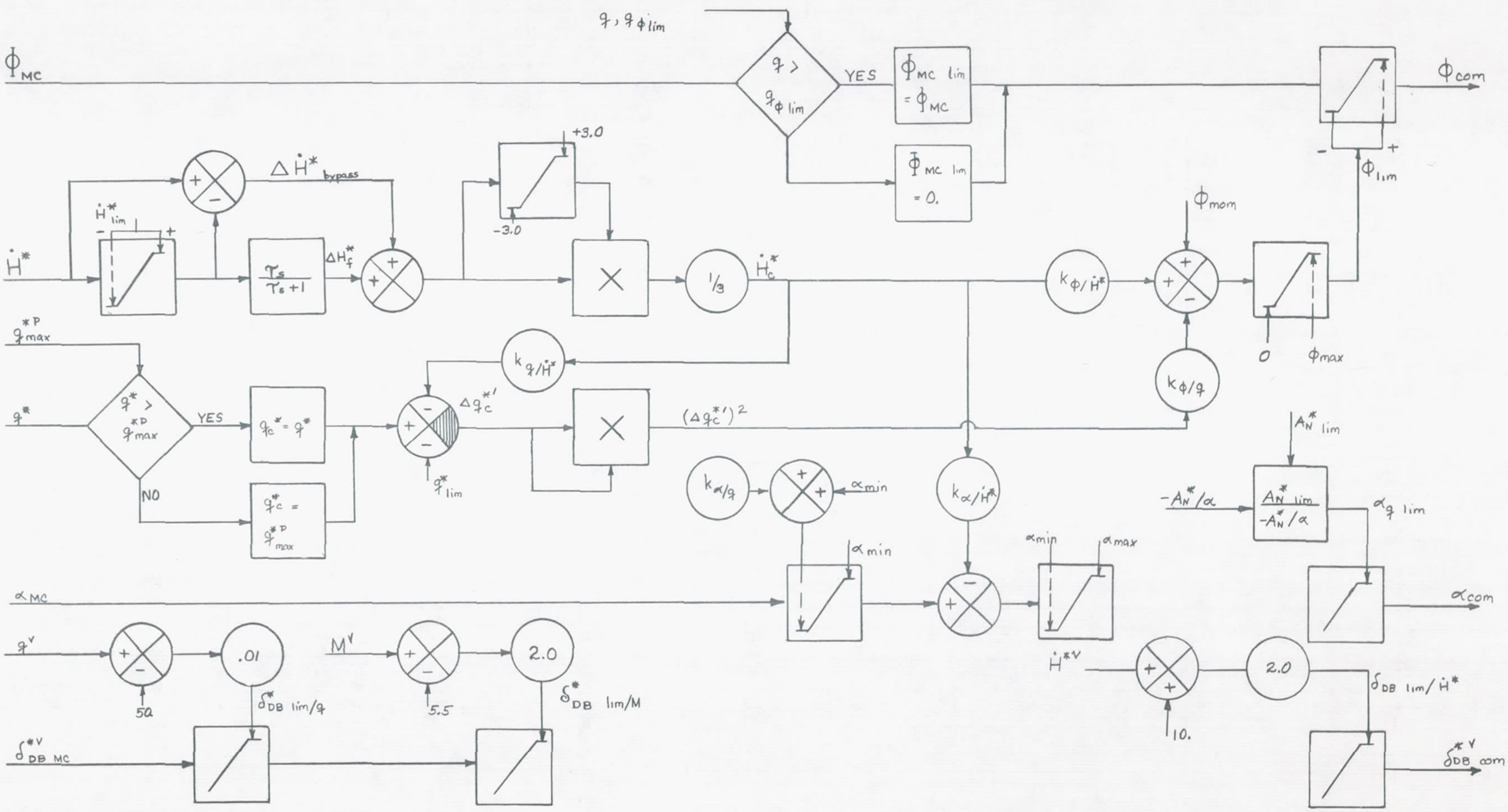


Figure 6.— Block diagram of EMS constraint control loops.

If control loops usage indicator equals zero (being used for vehicle),

$$q = q^{V}$$

$$\dot{H}^{*} = \dot{H}^{*V}$$

$$\Delta\dot{H}^{*}_{prev} = \Delta\dot{H}^{*V}_{prev}$$

$$\Delta\dot{H}_{f\ prev} = \Delta\dot{H}^{V}_{f\ prev}$$

$$M = M^{V}$$

$$\delta^{*}_{DB} = \delta^{*V}_{DB\ rl}$$

$$\Delta t = \Delta t^{V}$$

If control loops usage indicator equals one (being used for predictor),

$$q = q^{P}$$

$$\dot{H}^{*} = \dot{H}^{*P}$$

$$\Delta\dot{H}^{*}_{prev} = \Delta\dot{H}^{*P}_{prev}$$

$$\Delta\dot{H}^{*}_{f\ prev} = \Delta\dot{H}^{*P}_{f\ prev}$$

$$M = M^{P}$$

$$\delta^{*}_{DB} = \delta^{*P}_{DB\ rl}$$

$$\Delta t = \Delta t^{P}$$

After these parameters have been set, they are used in the control loops in an identical manner for the vehicle and predictor, except as otherwise noted.

Modification and Shaping of Constraint Parameters

As can be seen from Figure 6, both the damping parameter and dynamic pressure are used in control loops on the angle of attack and bank angle. However, it can also be seen that neither of these parameters are used in their direct form; but instead are modified before being used in the control loops. This modification changes the effective gains in the control loops in a manner that improves the stability of the control.

The damping parameter is modified by filtering and shaping. The filter consists of a limiter which limits the amount of the damping parameter that is filtered, a washout filter, and a bypass loop which bypasses the amount in excess of the limit around the filter and adds it back to the filtered increment.

The equations for the limit are,

$$\Delta\dot{H}^* = \dot{H}^*_{lim} - |\dot{H}^*|$$

$$\Delta\dot{H}^*_{f\ input} = \dot{H}^* \quad \text{and}$$

$$\Delta\dot{H}^*_{bypass} = 0 \qquad\qquad , \text{ if } \Delta\dot{H}^* > 0$$

$$\Delta\dot{H}^*_{f\ input} = \dot{H}^*_{lim} \text{ and}$$

$$\Delta\dot{H}^*_{bypass} = \Delta\dot{H}^* \operatorname{sgn}(\dot{H}^*), \text{ if } \Delta\dot{H}^* \leq 0$$

The washout filter of the form, Ts/(Ts + 1), is mechanized as a discrete difference equation as follows.

If previous history indicator equals zero (no previous history available)

$$\Delta\dot{H}^*_f = \Delta\dot{H}^*_{input}$$

If previous history indicator equals one (previous history available)

$$\Delta\dot{H}^*_f = T_{\dot{H}^*} (\Delta\dot{H}^*_{input} - \Delta\dot{H}^*_{prev} + \Delta\dot{H}^*_{f\ prev})/(T_{\dot{H}^*} + \Delta t)$$

The total filtered damping parameter is computed as,

$$\dot{H}^*_f = \Delta\dot{H}^*_f + \Delta\dot{H}^*_{bypass}$$

The damping parameter is then shaped by squaring it whenever it is less than three in magnitude,

$$\dot{H}^*_c = \dot{H}^*_f|\dot{H}^*_f| / 3. \quad , \text{ if } |\dot{H}^*_f| < 3.$$

$$= \dot{H}^*_f \quad , \text{ if } |\dot{H}^*_f| \geq 3.$$

The shaped damping parameter, $\dot{H}^*_c$, is then the parameter which is actually used in the damping control loops.

The dynamic pressure parameter which is used when the control loops are being used for the vehicle is the larger of the current nondimensional vehicle dynamic pressure or the predicted maximum nondimensional dynamic pressure at the future pullout, if one exists. When the control loops are being used for the predictor, the dynamic pressure parameter used is the current nondimensional dynamic pressure on the prediction.

$$q^* = q/q_{max}$$

where

$$q_{max} = 1600 \text{ psf}$$

If the control loops are being used for vehicle,

$$q_c^* = q^* \quad , \text{ if } q^* \geq q_{max}^{*P}$$

$$= q_{max}^{*P} \quad , \text{ if } q^* < q_{max}^{*P}$$

If the control loops are being used for predictor,

$$q_c^* = q^*$$

In either case, the nondimensional dynamic pressure parameter which is used is modified by the addition of a lead term as follows.

$$\Delta q^*_{lead} = - k_{q/H^*} H_c^*$$

$$q_c^{*\prime} = q_c^* + \Delta q^*_{lead}$$

This modified dynamic pressure parameter is then checked agianst a limit which is set below the maximum allowable value and, whenever it is greater than this limit, it is shaped and used to modify the maneuver commands.

$$\Delta q_c^* = (q_c^{*\prime} - q^*_{lim})^2 \quad , \text{ if } q_c^{*\prime} > q^*_{lim}$$

$$= 0 \qquad\qquad , \text{ if } q_c^{*\prime} \leq q^*_{lim}$$

Bank Angle Constraints

As can be seen from Figure 6, the modified damping parameter, H_c^*, and the modified dynamic pressure increment, Δq_c^*, are first used to modulate and limit the bank angle maneuver command. This is always done for the vehicle commands and it is done for the predictor commands, except when a maximum range prediciton is being made. In the latter case, the constraint control loops do not alter the bank angle maneuver command since it is zero and, therfore, the constraint bank angle command, ϕ_c, is set equal to the maneuver command, ϕ_{mc}, and this section of the programs is bypassed.

In the constraint control loops, the bank angle maneuver command is first limited to zero if the dynamic pressure is less than a value at which the control surface effectiveness of the X-15 becomes marginal for controlling roll.

$$\phi_{c\ell} = \phi_{mc} \qquad , \text{ if } q > q_{\phi\ lim}$$

$$= 0 \qquad , \text{ if } q \leq q_{\phi\ lim}$$

If the maneuver command is not limited here, the programs then use the damping and dynamic pressure constraint parameters to modulate the maximum allowable bank angle as follows.

$$\phi_{max} = \phi_{nom} + k_{\phi/\dot{H}^*}\dot{H}_c^* - k_{\phi/q}\Delta q_c^*$$

From the above equations, it can be seen that these constraint control loops reduce the maximum allowable bank angle whenever the vehicle is falling too fast and/or the dynamic pressure approaches the maximum allowable value. To prevent this bank angle limit from becoming negative or from exceeding the absolute bank angle limit that is imposed on the EMS by the X-15 adaptive flight control system, it is first limited before being used to limit the bank angle maneuver command.

$$\phi_{max\ell} = \phi_{max} \text{ limited to: } 0 \leq \phi_{max} \leq \phi_{max\ abs}$$

$$\phi_c = \phi_{c\ell} \text{ limited to: } -\phi_{max\ell} \leq \phi_{c\ell} \leq \phi_{max\ell}$$

Angle of Attack Constraints

The modified damping and dynamic pressure parameters are always used in the constraint control loops to modulate and limit the angle of attack maneuver commands for both the vehicle and predictor. In these loops, the dynamic pressure is first used to form a lower limit on the angle of attack which increases the minimum allowable angle of attack whenever the dynamic pressure parameter approaches critical.

$$\Delta\alpha_{lim/q} = k_{\alpha/q}\Delta q_c^*$$

$$\alpha_{lim/q} = \alpha_{min} + \Delta\alpha_{lim/q}$$

The angle of attack maneuver command is then limited as follows.

$$\alpha_{q\ell} = \alpha_{mc} \text{ limited to: } \alpha_{min/q} \leq \alpha_{mc} \leq \alpha_{max}$$

The limited angle of attack maneuver command is then modulated by a damping loop which increased the angle of attack if the vehicle is falling too rapidly and decreased it if the vehicle is rising too rapidly.

$$\alpha_{(q\ell + \dot{H}^*)} = \alpha_{q\ell} + k_{\alpha/\dot{H}^*} \dot{H}_c^*$$

This modulated angle of attack is then limited to prevent the damping loop from driving it above or below the maximum and minimum angle of attack, respectively.

$$\alpha(q\ell + \dot{H}^* + \ell) = \alpha(q\ell + \dot{H}^*) \text{ limited to:}$$

$$0 \leq \alpha(q\ell + \dot{H}^*) < \alpha_{max}$$

If the constraint control loops are being used to modulate and limit the vehicle commands, the damped and limited angle of attack is then limited by a normal acceleration control loop[1].

In this control loop, the normal acceleration that would exist if this angle of attack were used is computed and checked against the maximum acceleration limit. If the computed acceleration exceeds the limit, the angle of attack that results in a computed acceleration equal to the limit is computed and the angle of attack command is set equal to this value. If the computed acceleration is less than the limit, the angle of attack is not modified.

$$(A_N^V/q_o) = [(\partial A_N^V/\partial\alpha)/g_o]\ \alpha(q\ell + \dot{H}^* + \ell)$$

If

$$(A_N^V/g_o) > (A_{N\ max}/q_o),$$

$$\alpha_c = (A_{N\ max}/g_o)/\partial A_N^V/\partial\alpha)/q_o$$

If

$$(A_N^V/g_o) \leq (A_{N\ max}/g_o),$$

$$\alpha_c^V = \alpha(q\ell + \dot{H}^* + \ell)$$

If the constraint control loops are being used to modulate and limit the predictor commands, the modulated and limited angle of attack is also limited by a normal acceleration control loop. The equations for it are identical to those of the vehicle loop except that they are in nondimensional form.

---

(1) In the SDS 930 program, this loop is a part of subroutine EMC X-15.

$$A_N^{*P} = (\partial A_N^*/\partial\alpha)^P \; \alpha(q\ell + \dot{H}^* + \ell)$$

If

$$A_N^{*P} > A_{N\ max}^* \quad ,$$

$$\alpha_c^P = A_N/(\partial A_N^*/\partial\alpha)^P$$

If

$$A_N^{*P} \leq A_{N\ max}^*$$

$$\alpha_c^P = \alpha(q\ell + \dot{H}^* + \ell)$$

Return Logic

Since this subroutine is used to modulate and limit both the vehicle and predictor maneuver commands, a certain amount of logic is necessary to set the outputs of this subroutine equal to those for the vehicle when it is being used for the predictor. The outputs which are set are as follows:

If control loop usage indicator equals zero (being used for vehicle),

$$\Delta\dot{H}^{*v}_{prev} = \Delta\dot{H}_{prev}$$

$$\Delta\dot{H}^{*v}_{f\ prev} = \Delta\dot{H}_{f\ prev}$$

$$\phi^{v}_{c} = \phi_{c}$$

In addition, a vehicle previous history indicator, KOPE, must be set to one to indicate that previous history is now available for the time dependent computations in this subroutine.

If the control loop usage indicator equals one (being used for predictor),

$$\Delta\dot{H}^{*P}_{prev} = \Delta\dot{H}_{prev}$$

$$\Delta\dot{H}_{f\ prev} = \Delta\dot{H}_{f\ prev}$$

$$\phi^{P}_{c} = \phi_{c}$$

In addition, a predictor previous history indicator, KODE, must be set to one as for the vehicle.

(2) Control Loops on Drag Brake (Part of subroutine EMCX in SDS-930 program; part of subroutine OUTPTGEN in ALERT program.

As shown in Figure 6, three constraint control loops are used to limit the drag maneuver command. The first control loop limits the drag brake command to zero if the Mach number is greater than 5.5 since lateral control problems can be encountered if the drag brakes are deflected at higher Mach numbers.

$$\delta^{*v}_{DB\ lim/M} = 2\ (5.5 - M^{v})$$

The second control loop limits the drag command to zero if the dynamic pressure is less than 50 psf since the drag brakes are not effective at low dynamic pressure.

$$\delta^{*v}_{DB\ lim/q} = .01\ (q^{v} - 50.)$$

The last control loop limits the drag brake command to zero if the vehicle is rising rapidly since it is not desired to deflect the drag brakes when the X-15 is climbing to altitude.

$$\delta^{*v}_{DB\ lim/H^*} = .2\ (\dot{H}^{*v} + 10.)$$

The dominant limit on the drag brake maneuver command is the minimum of these three limits;

$$\delta^{*v}_{DB\ lim} = \mathrm{Min}\ (\delta^{*v}_{DB\ lim/M}, \delta^{*v}_{DB\ lim/q}, \delta^{*v}_{DB\ lim/H^*})$$

To provide absolute limits on the drag brake deflection, this limit is limited as follows:

$$\delta^{*v}_{DB\ lim} \text{ is limited to: } -0.5 \leq \delta^{*v}_{DB\ lim} \leq 1.0$$

This limit is then used to limit the drag brake maneuver commands as follows:

$$\delta^{*v}_{DBc} = \delta^{*v}_{DB\ mc} \text{ limited to: } -0.5 \leq \delta^{*v}_{DB\ mc} \leq \delta^{*v}_{DB\ lim}$$

6. Transformation of EMS Outputs (Part of subroutine EMCX in SDS-930 program; part of OUTPTGEN in ALERT program)

Although all of the equations and logic for generating the basic EMS outputs have been presented at this point, a certain amount of computation is necessary to transform these to the form required by the X-15 displays and automatic flight control system. The transformations which are required are as follows:

a. Bank Angle Command

The bank angle command which is generated by the EMS is relative to the vehicle velocity vector. Since the X-15 roll attitude is displayed relative to the longitudinal body axis and since the X-15 automatic flight control system requires a roll signal relative to the longitudinal body axis, this bank angle command must first be transformed to body axis. The equations for this are as follows:

$$\sin\Theta^V = \frac{(\dot{h}^V\cos\alpha^V + V_H\sin\alpha^V\cos\phi_c^V}{V^V \qquad \alpha}$$

$$\cos\Theta^V = \sqrt{1 - (\sin\Theta^V)^2}$$

$$\sin\phi_B{}^V{}_c = (V_H^V/V^V)\ \sin\phi_c^V/\cos\Theta^V$$

$$\cos\phi_B{}^V{}_c = \sqrt{1 - (\sin\phi_B{}^V{}_c)^2}$$

$$\phi_B{}^V{}_c = 57.3\ \arctan\ (\sin_B{}^V{}_c/\cos\phi_{Bc}^V)$$

In addition to preventing noise in the roll command from feeding through to the roll command needle on the X-15 three axis attitude indicator and to the automatic flight control system, if it is being used, the EMS roll command relative to the X-15 longitudinal body axis is rate limited before being transmitted to the X-15 displays and automatic flight control system. The equations for this are as follows:

$$\Delta\phi_{max} = \dot{\phi}_{max}\Delta t^{v}$$

$$\phi^{v}_{Bc\ rl} = \phi^{v}_{Bc} \text{ limited to:}$$

$$\phi^{v}_{B\ prev} - \Delta\phi_{max} \leq \phi^{v}_{Bc} \leq \phi^{v}_{B\ prev} + \Delta\phi_{max}$$

$$\phi^{v}_{B\ prev} = \phi^{v}_{Bc\ rl}$$

b. Angle of Attack Command

In generating the angle of attack command in the EMS, it is assumed that no significant phugoid transient will be introduced if the X-15 angle of attack is held at the command value while the vehicle bank angle is reversed. However, if the pilot reverses the vehicle bank angle at a low roll rate or if the automatic flight control system, which limits the EMS roll rate command to 14°/sec, is used to reverse the vehicle bank angle, a large phugoid transient can result if the X-15 angle of attack is held at the command value. To prevent this from happening, a transformation has been included in the EMS which reduces the angle of attack command in a manner that holds the vertical acceleration constant during a bank reversal. The equation for this transformation is as follows:

$$\alpha^{v}_{cl} = \alpha^{v}_{c} \cos \phi^{V}_{Bc} / \cos \phi^{v}_{Bc\ rl}$$

In addition, the angle of attack command is rate limited for the same reasons the bank angle command is.

$$\Delta\alpha_{max} = \dot{\alpha}_{max}\ \Delta t^{V}$$

$$\alpha^{v}_{c\ rl} = \alpha^{v}_{cl} \text{ limited to:}$$

$$\alpha_{c\ prev} - \Delta\alpha_{max} \leq \alpha_{cl} \leq \alpha_{z\ prev} + \Delta\alpha_{max}$$

$$\alpha_{c\ prev} = \alpha_{c\ rl}$$

c. Drag Brake Command

Since only two discrete indicators are available for displaying the EMS drag brake command in the X-15 cockpit, the continuous drag brake command that is generated by the EMS is transformed to a three position, discrete signal in the EMS before being transmitted to the X-15 displays. Two dead zones are included in this transformation to prevent the command from chattering when it is near one of the switch points. The form that the drag brake command takes after passing through this transformation is illustrated in Figure 7.

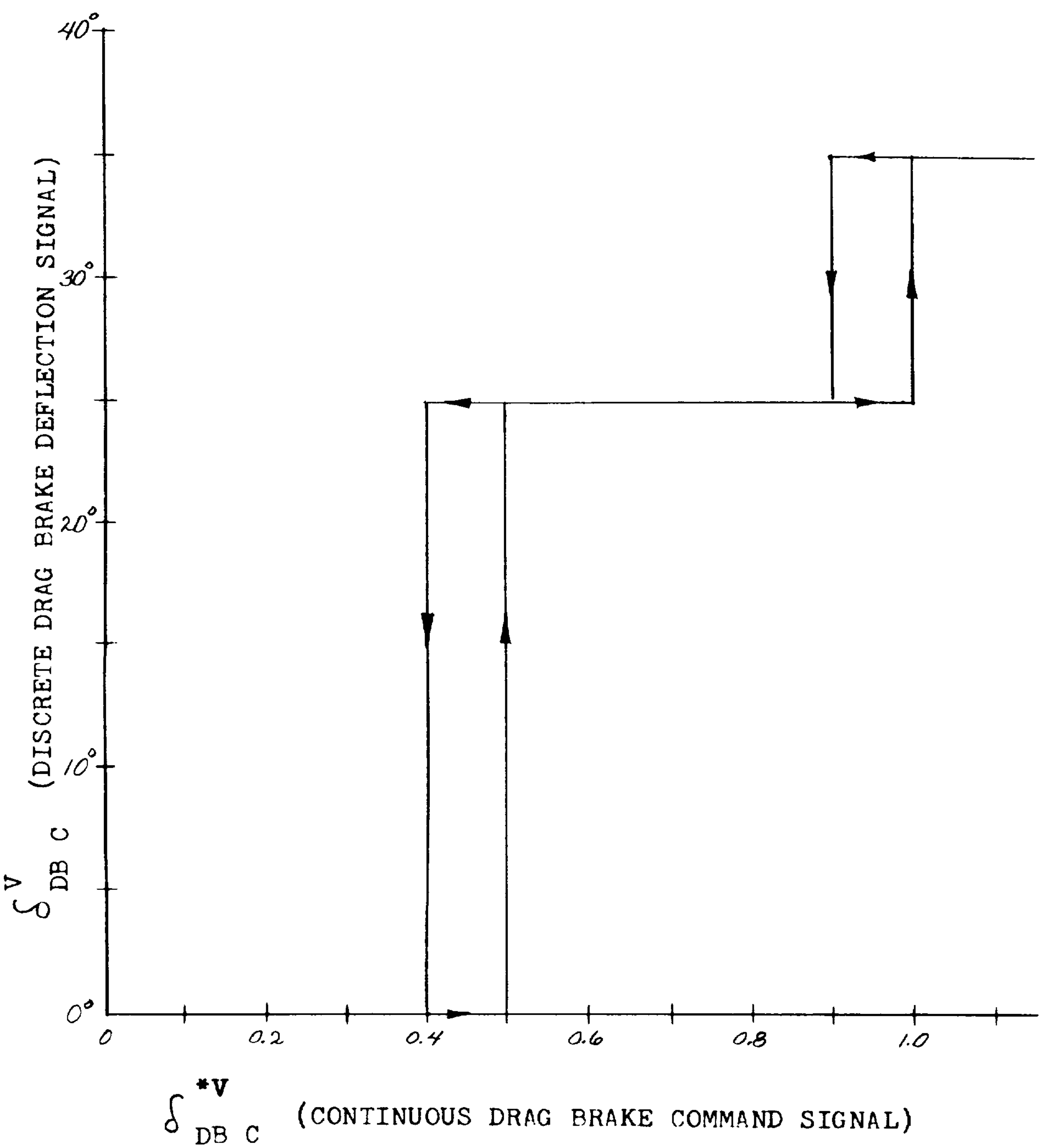


Figure 7.— Generation of discrete drag brake deflection signal.

The logic and equations for this transformation are as follows;

If

$$(\delta^{*v}_{DBc} + \delta^{*v}_{DB\ DZ}) < .5$$

$$\delta^{*}_{DB\ DZ} = 0$$

$$\delta^{*}_{DB\ max} = 0$$

$$\delta^{v}_{DBc} = 0$$

If

$$0.5 \leq (\delta^{*v}_{DBc} + \delta^{*}_{DB\ DZ}) < 1.0$$

$$\delta^{*}_{DB\ DZ} = .1$$

$$\delta^{*}_{DB\ max} = 0$$

$$\delta^{v}_{DBc} = 0.7\ \delta_{DB\ max}$$

If

$$(\delta^{v}_{DBc} + \delta^{*}_{DB\ DZ}) \geq 1.0 \text{ and } \delta^{*}_{DB\ max} = 0 \text{ and } \delta^{*}_{DBc} < 1.0,$$

$$\delta^{v}_{DBc} = .7\ \delta_{DB\ max}$$

If

$$(\delta^{*v}_{DBc} + \delta^{*}_{DB\ DZ}) \geq 1.0 \text{ and } \delta^{*}_{DB\ max} = 0 \text{ and } \delta^{*}_{DBc} \geq 1.0,$$

$$\delta^{*}_{DB\ max} = 1.0$$

$$\delta^{v}_{DBc} = \delta_{DB\ max}$$

If

$$(\delta^{*v}_{DBc} + \delta^{*}_{DB\ DZ}) \geq 1.0 \text{ and } \delta^{*}_{DB\ max} = 1.0,$$

$$\delta^{v}_{DBc} = \delta_{DB\ max}$$

D. Predictor Computations

The predictor computations are comprised of a predictor initialization section, a predictor which is a three degree of freedom, point mass simulation of the X-15 in differential equation form, a prediction processing and phasing section, and a coefficient set up section. The predictor initialization section sets the initial predictor flight conditions equal to the X-15 flight conditions. The predictor integrates the differential equations for the X-15 model from these flight conditions to predict the maneuvering capabilities of the X-15 in terms of maximum and minimum range and maximum cross range and the maximum dynamic pressure at the future pullout, if one exists, on reentry. The predictor processing and phasing section computes the dimensional GAA parameters from the outputs of the predictor and sets up the inputs for the coefficient set up section. It also sets a prediction type indicator and a predictor stopping condition indicator which control the phasing of the predictor from one type of prediction to another. The coefficient set up section utilizes the results of consecutive predictions to set up coefficients for the GAA entrapolator.

1. Preliminary Predictor Initialization (Part of subroutine EMCX in SDS-930 program, section PRELINIT in ALERT program)

   In this section, the initial predictor flight conditions are set equal to the vehicle flight conditions as follows:

$$V_o^P = V^V$$

$$h_o^P = h^V$$

$$\gamma^V = \arctan\,(\dot{h}^V/V_H^V)$$

$$\gamma_o^P = \gamma^V$$

$$\alpha_o^P = \alpha^V$$

In addition, the value of the independent variable, which is used in the GAA entrapolator, at the time that the predictor is initialized is computed.

$$E_o^P = E^V$$

$\Delta I_{off}^P = E_o^P - \Delta I_{on}^V$, if engine firing code indicates engine not firing

ΔI_{off}^P is unchanged, if engine firing code indicates engine is firing

$$I^P = E_o^P - \Delta I^P + k_t\ t^V$$

These coefficients for the GAA entrapolator are later set up versus this independent variable in the coefficient set up section.

As a final step in this section, the predictor input code is set to one to indicate that the latest available flight conditions have been used to initialize the predictor.

2. Predictor (Subroutine PX15 in SDS-930 program; subroutine PREDCOMP in ALERT program)

As mentioned previously, since the time required for the predictor to predict any one of the range maneuvering capabilities of the X-15 can be greater than the time period between updates of the vehicle commands, provisions have been made in the program for interrupting the predictor when it is time to compute new vehicle commands. Therefore, when the predictor is entered, the predictor status code is first checked to determine if the predictor is being entered for a new predictor or whether it is being reentered to complete a prediction that was interrupted. If the predictor status code is zero, the predictor is being entered for a new prediction and the programs branch to an initialization section. If the predictor status code is one, the predictor is being reentered to continue a prediction that was interrupted and the programs branch directly into the equations of motion.

a. Initialization

In this section, the predictor flight conditions are initialized to the initial predictor flight conditions as follows:

$$V^P = V_o^P$$

$$h^P = h_o^P$$

$$\gamma^P = \gamma^P$$

$$\alpha^P = \alpha_o^P$$

The remaining predictor flight parameters are initialized at predetermined values as follows:

$$t^P = 0$$

$$R^P = 0$$

$$\lambda^P = \pi/2$$

$$\mu^P = 0$$

$$\xi^P = 0$$

$$\phi^P = 0$$

In addition, the previous values of predictor altitude and density, which are used in an incremental computation of predictor density, are initialized here since no previous history is available.

$$h^P_{prev} = h_{top} \ , \ \text{if } h^P > h_{top}$$

$$= h^P \ , \ \text{if } h^P \le h_{top}$$

$$\rho^P_{\rho rev} = \rho^P_o$$

The sine and cosine of the bank angle are set in this section since they are known when the angle is zero.

$$\sin \phi^P = 0$$

$$\cos \phi^P = 1.0$$

Several integration parameters are also set here. An integration reset code which is used to reset the integration when the predictor Mach number passes through one is set to zero since no previous history on the predictor Mach number is available. A gain on the second derivative terms in the integration is also set to zero because there is no previous history available for forming these derivatives.

$$k_{\ddot{x}} = 0.$$

The initial value of the predictor integration interval is also initialized here

$$\Delta t^P = 0.75$$

b. Differential Equations of Motion

The differential equations that are contained in the predictor are an earth relative set for the motion of a point mass, under the influence of aerodynamic forces, in the earth's atmosphere. Since the manner in which these equations are mechanized in the programs makes it difficult to see the basic form of them, they will be shown here for clarity:

$$\dot{h} = V \sin \gamma$$

$$\dot{V} = (D/m) - g \sin\gamma$$

$$\dot{\gamma} = \frac{(L/m) \cos\phi - g \cos\gamma}{V}$$

$$\dot{\lambda} = \frac{V \cos\gamma \sin\xi}{r_e + h}$$

$$\dot{\mu} = \frac{V \cos\gamma \cos\xi}{r_e + h}$$

$$\dot{\xi} = \frac{(L/m) \sin\phi}{V \cos\gamma}$$

The actual mechanization of these equations in the programs is as follows. The sine and cosine of the predictor flight path angle and the predictor attitude rate are first computed.

$$\sin \gamma^P = \sin (\gamma^P)$$

$$\cos \gamma^P = \cos (\gamma^P)$$

$$\dot{h}^P = V^P \sin \gamma^P$$

The predictor altitude is then compared with an altitude, h_{top}, corresponding to the top of the appreciable atmosphere. If the predictor is above this altitude, it is assumed that all of the aerodynamic forces are insignificant. In this case, these forces are set to zero and all the computations pertaining to them are bypassed.

$$(L/m)^P = 0$$

$$(D/m)^P = 0$$

$$(L/m)^P_v = 0$$

If the predictor is below this altitude, the aerodynamic forces are computed. In these computations, the density is first computed in an incremental manner as follows:

$$\beta^P = 6.55 \times 10^{-5} - 1.72 \times 10^{-10} h^P, \text{ if } h^P > 97500.$$

$$= 4.85 \times 10^{-5}, \text{ if } 4500 \leq h^P \leq 97500.$$

$$= 2.9 \times 10^{-5} + 2.05 \times 10^{-10} h^P + 5.05 \times 10^{-5} (h^P)^2, \text{ if } h^P < 45000.$$

$$\Delta h^P = h^P - h^P_{prev}$$

$$\rho^P = \rho^P_{prev} \; e^{-\beta^P \; \Delta h^P}$$

$$h^P_{prev} = h^P$$

$$\rho^P_{prev} = \rho^P$$

The dynamic pressure and a dynamic pressure term are then computed.

$$q^P = .5 \; \rho^P \; (V^P)^2$$

$$(qS/m)^P = q^P S/m$$

The Mach number, which is requried to determine the lift and drag coefficients, is computed as,

$$V_s = f_1 \; (h^P)$$

$$M^P = V^P/V_s$$

The predictor angle of attack and bank angle commands are then computed at this point in the programs. Since these computations are quite lengthy, they will be discussed separately in a later section so that they will not detract from the equations of motion being presented here. Once they are computed, the lift and drag coefficients are computed from polynomial functions as follows:

$$C_{L_\alpha},\ C_{D_o},\ C_{D_{C_L^2}} = f_4\ (M^P)$$

$$C_L^P,\ C_D^P = f_5\ (\alpha^P,\ C_{L_\alpha},\ C_{D_o},\ C_{D_{C_L^2}})$$

The lift and drag accelerations are then computed as

$$(L/m)^P = (qS/m)^P\ C_L^P$$

$$(L/m)_v^P = (L/m)^P \cos\ \phi^P$$

$$(D/m)^P = (qS/m)^P\ C_D^P$$

At this point, the computation of the aerodynamic accelerations are completed. For the case where these computations were bypassed, the program branches to this point and in both cases, the derivatives for the longitudinal flight path variables are computed.

$$\dot{V}^P = -\ (D/m)^P - g \sin\ \gamma^P$$

$$\dot{\gamma}^P = \frac{(L/m)_v^P - g \cos\ \gamma^P}{V}$$

$$\dot{R} = k_{nm/ft}\ V^P \cos\ \gamma^P$$

If a minimum range or maximum cross range prediction is being made, the derivatives for the lateral flight path equations are then computed. If a maximum range prediction is being made, these computations are bypassed since there is no lateral maneuvering on this type of prediction. The lateral equations are as follows:

$$\sin \xi^P = \sin (\xi^P)$$

$$\cos \xi^P = \cos (\xi^P)$$

$$\dot{\lambda}^P = \frac{V^P \cos \gamma^P \sin \xi^P}{r_e}$$

$$\dot{\mu}^P = \frac{V^P \cos \gamma^P \cos \xi^P}{r_e}$$

$$\dot{\xi}^P = \frac{(L/m)^P \sin \phi^P}{V^P \cos \gamma^P}$$

c. Integration

A second order integration method, based on the first three terms of a Taylor series expansion, is used in the EMS predictor to integrate the flight path derivatives. The form of this method is,

$$x_{t + t} = x_t + \dot{x}_t \, \Delta t + k_{\ddot{x}} \, \ddot{x}_t \, \Delta t^2$$

Since the second derivatives of the flight path variables which are integrated cannot be computed easily, they are approximated by a first order divided difference of the form.

$$\ddot{x}_t = (\dot{x}_t - \dot{x}_{t - \Delta t \, prev})/\Delta t \; prev$$

When this is substituted into the above integration equation, the form of the equation which is used in the program is obtained.

$$x_t + \Delta t = x_t + \dot{x}_t \Delta t + \frac{k_{\ddot{x}} \, (\dot{x}_t - \dot{x}_{t - \Delta t \, prev}) \Delta t^2}{\Delta t_{prev}}$$

For example, the equation for integrating altitude rate is,

$$h^p = h^p + \dot{h}^P \Delta t^P + \frac{k_{\ddot{x}} (\dot{h}^P - \dot{h}^P_{prev})(\Delta t^P)^2}{\Delta t_{prev}}$$

The equations for integrating all of the other flight path variables are identical in form to the above equation. These equations are solved for all the flight path variables on each prediction except for the lateral integration equations when a maximum range prediction is being made.

The gain, $k_{\ddot{x}}$, on the second derivative term in these equations is normally set to one half. However, when the predictor is first initialized and no previous history is available, this gain is set to zero as mentioned previously. In this case, a first order integration results for the first integration step. After this first step, previous history is available for forming the second derivatives and the gain is set back to its normal value. The gain then remains at this value unless Mach number passes through one. In this case, the integration is reset by setting this gain to zero. This is done to prevent the step changes in the aerodynamic coefficients which occur at Mach one from causing the computed second derivatives from approaching infinity if the integration interval is near zero.

The equations and logic for this are as follows:

If integration reset code is zero and $M^P > 1.0$,

$k_{\ddot{x}} = 0.5$

If integration reset code is zero and $M^P \leq 1.0$,

$k_{\ddot{x}} = 0$

integration reset code = 1

If integration reset code is one and $M^P \geq M_{lim}$,

$k_{\ddot{x}} = 0$

integration reset code = 0

If integration reset code is one and $M^P < M_{lim}$ and $M^P \geq 0.99$

$$k_{\ddot{x}} = 0.5$$

$$M^P = 0.99$$

If integration reset code is one and $M^P < M_{lim}$ and $M^P < 0.99$,

$$k_{\ddot{x}} = 0$$

The integration is always reset in this manner except when the predictor is above the top of the appreciable atmosphere. In this case, the gain on the second derivative terms in the integration is set to one half and the reset logic is bypassed.

In addition to the integration method, the integration interval is also an important factor in the predictor since it determines how rapidly predictions can be made. The EMS predictor uses a variable integration interval which is always made as large as possible for predictions that are accurate to within one percent. The integration interval is based on the velocity, the lift acceleration, and the dimensional and nondimensional rate of change in the vertical component of the lift acceleration. It is mechanized such that the integration interval is large if the lift acceleration is near equilibrium and is not changing rapidly. However, if the lift acceleration is far from equilibrium or, if it is changing rapidly, the integration interval is small.

The equations and logic for computing the integration interval are always solved except on the first integration step after the predictor is initialized or when the integration is reset. In these cases, the integration interval is set to 1.5 sec and the integration interval computations are bypassed.

When the integration interval computations are made, the rate of change of the vertical component of the lift acceleration is first computed as follows:

$$(\dot{L/m})_v^P = \frac{[(L/m)_{v\ 1}^P - (L/m)_{v\ 1\ prev}^P]}{\Delta t_{prev}^P}$$

where $(L/m)_{v\ 1}^P = (L/m)_v^P$ limited to:

$$(L/m)_v^P \geq .5$$

The nondimensional rate of change of the vertical component of lift acceleration is computed as,

$$(\dot{L}/m)_v^{*P} = (\dot{L}/m)_{v\ 1}^P \ / \ (L/m)_{v\ 1\ prev}^P$$

where: $(\dot{L}/m)_{v\ 1}^P = (\dot{L}/m)_v^P$ limited to;

$$(\dot{L}/m)_v^P \geq 4.$$

$$(L/m)_{v\ 1\ prev}^P = (L/m)_{v\ 1}^P$$

The integration interval is then computed as,

$$\Delta t^P = \frac{k_{\Delta t}}{g + |(L/m)^P - g| + 40.\ (\dot{L}/m)_v^P + 550.\ (\dot{L}/m)_v^{*P}}$$

where: $k_{\Delta t} = k_{o\ \Delta t}$, if $V^P > 1333.$

$$= \frac{k_{o\ \Delta t}\ V^P}{1333.} - (1333 - V^P),$$ if $V^P \leq 1333.$ and integration reset code = 0

$$= \frac{k_{o\ \Delta t} V^P}{1333.},$$ if $V^P \leq 1333.$ and integration reset code = 1

After the integration interval is computed, it is filtered if it is increasing as follows:

If $\Delta t^P \leq \Delta t^P_{prev}$,

$$\Delta t^P_{prev} = \Delta t^P$$

If $\Delta t^P = \Delta t^P_{prev}$,

$$\Delta t^P = (\Delta t^P + 3.\ \Delta t^P_{prev})/4.$$

$$\Delta t^P_{prev} = \Delta t^P$$

d. Stopping Conditions

Once the integration of the flight path derivatives over the current integration interval is completed, the stopping conditions are checked to determine if the prediction has been completed or if the prediction is being interrupted. If the prediction is not completed or interrupted, the programs branch back to the beginning of the equations of motion section and the entire computational procedure just described is repeated for another integration step. This is then continued until the prediction is either completed or interrupted.

If the prediction is either completed or interrupted, the programs set predictor status code and exit. To determine if the prediction is completed, the predictor energy is first compared as,

$$E^P = (V^P)^2 + 2\ g\ \ h^P \ ,$$

and compared with the terminal energy, E_{final}. If the predictor energy is less than or equal to the terminal energy, the prediction is completed regardless of whether the desired stopping condition has been reached or not. In this case, the programs branch to the prediction completed section.

If the predictor energy is greater than the terminal energy, the programs go on to determine if the desired stopping conditions have been met. On maximum range prediction or on a maximum cross range prediction, the prediction is completed whenever the predictor energy becomes less than the predictor stopping energy.

If $E^P > E^P_{stop}$, continue prediction

$E^P \leq E^P_{stop}$, branch to prediction completed section.

On a minimum range prediction, the prediction is completed after the predicted lateral flight path has turned through 180°.

If $\xi^P < \pi$, continue prediction

$\xi^P \geq \pi$, branch to prediction completed section

If none of the stopping conditions have been met and the prediction is to be continued, the interrupt code is first checked to determine if the prediction is being interrupted. If the interrupt code is zero, time is still available for predicting and the programs branch back to the beginning of the equations of motion section as mentioned previously. If the interrupt code is one, the time between updatings of the vehicle commands which is available for predicting has been depleted. In this case, the predictor status code is set to one to indicate that the current prediction was interrupted before it was completed and the programs exit the predictor.

If any of the stopping conditions have been met, the predictor status code is set to zero to indicate that the current prediction has been completed. The final values of the flight conditions at the end of the prediction are then set as follows and the predictor is exited.

$$R^P_{final} = R^P$$

$$\lambda^P_{final} = \lambda^P$$

$$\mu^P_{final} = \mu^P$$

$$\xi^P_{final} = \xi^P$$

$$E^P_{final} = E^P$$

e. Predictor Command Computations

(1) Maneuver Commands part of subroutine COMX in SDS-930 program, part of subroutine COMNDGEN in ALERT program)

The maneuver commands for the predictor are predetermined commands which tend to maximize the maneuvering capability of the vehicle. A separate set of angle of attack and bank angle maneuver commands are stored in the computer programs for each type of prediction. By using these commands, the predictor can predict the limits of the X-15's maneuvering capability, GAA, in terms of maximum range, minimum range, and maximum cross range.

In computing these commands, the angle of attack for maximum lift to drag and the maximum useable angle of attack are computed first.

$$\alpha_{max} = f_2 \left(M^P, \delta^{*P}_{DB\ rl}, k^P_{\delta H}\right)$$

where: $\delta^{*P}_{DB\ rl}$ = rate limited deflection of predictor drag brakes (1)

$k^P_{\delta H}$ = fraction of allowable deflection of horizontal stabilizers (2)

$$\alpha_{(L/D)max} = f_3 \left(M^P\right)$$

(1) This parameter is always zero for the prediction since drag brakes are not employed on any of the predictions.

(2) See predictor constraint computations in section III-D-3-(5)-(b) for description of this parameter.

The specific set of commands which is used on any given prediction is determined by checking the prediction type code. If it is minus one, indicating that a maximum range prediction is being made, the maneuver commands are as follows:

$$\alpha^P_{mc} = \alpha_{(L/D)\ max}$$

$$\phi^P_{mc} = 0$$

If the prediction type code is zero, indicating that a minimum range prediction is being made, the maneuver commands are as follows:

$$\alpha^P_{mc} = 17. - 50.\ (\xi^P - \pi/2)$$

$$\phi^P_{mc} = 100.\ (1 - \xi^P/3.5)$$

If the prediction type code is one, indicating that a maximum cross range prediction is being made, the maneuver commands are as follows:

$$\alpha^P_{mc} = \alpha_{(L/D)\ max}$$

$$\phi^P_{mc} = k^P_\phi\ k_{\phi/R^*_c}\ [1.0 - (\xi^P/\pi/2)^2]$$

Regardless of the type of prediction being made, the prediction maneuver commands are limited as follows:

$$\alpha_{mc}^{P} \text{ is limited: } \alpha_{(L/D)\,max} \leq \alpha_{mc}^{P} \leq \alpha_{max}$$

$$\phi_{mc}^{P} \text{ is limited: } -\phi_{nom} \leq \phi_{mc}^{P} \leq +\phi_{nom}$$

(2) Constraint Control

As mentioned previously, the EMS constraint control loops are also used, in a manner identical to that for the X-15, to modulate and limit the predictor maneuver commands as required to damp out phugoid flight path oscillations and to insure that the vehicle constraints are not exceeded on the predictions. This is done to insure that the predicted GAA is an accurate indication of what the X-15 can attain. However, as for the vehicle, certain constraints which are used in the constraint control loops must be computed before the constraint control loop computations are made.

Damping and Constraint Computations

As for the vehicle, a nondimensional damping parameter, which is used in the control loops which damp out phugoid flight path oscillations, must be computed.

$$H^{*P} = 1.0 + \frac{[\beta^P (V^P)^2 + 2g] \sin \gamma^P}{\beta^P K_{\dot{H}}^*} \qquad (1)$$

where: $K_H^* = 2g/[\beta_o \ (L/D_{avg}] = \text{constant}$

A normal acceleration parameter must also be computed for the predictor. Since the predictor lift and drag coefficients are referenced to the predictor velocity, these must first be transformed to body axis to obtain the slope of the normal coefficient.

$$C^P_{L\ prev} = C^P_{L\alpha} \ \alpha^P_{prev}$$

$$C^P_{L\ prev} = C^P_{D_o} = C_{D_{C^2_L}} \ (C^P_{L\ prev})^2$$

$$C^P_{N\alpha} = \frac{(C^P_{L\ prev} \cos \alpha^P_{prev} + C^P_{D\ prev} \sin \alpha^P_{prev})}{\alpha^P_{prev}}$$

The slope of the normal coefficient is then limited, as it was for the vehicle.

$$C^P_{N\alpha} \text{ is limited to: } 0.0215 \leq C^P_{N\alpha} \leq 0.070$$

This limited coefficient is then used to compute the partial of the normal acceleration with respect to the angle of attack at the current point in the prediction. This normal

(1) Although the algebraic form of this computation is different than that for the vehicle, the computation itself is identical to that for the vehicle.

acceleration parameter is then used in the normal acceleration control loop for the predictor.

$$(\partial A_N^*/\partial\alpha)^P = -\frac{(qS/m)P\ C_{N\alpha}^P}{A_{N\ max}\ g_o}$$

As for the vehicle the maximum attainable angle of attack in the predictor is a function of the Mach number, the drag brake deflection, and the horizontal stabilizer deflection. Since, as mentioned previously, the predictor does not employ the drag brake on any prediction, the drag brake signal which is used to constrain the maximum angle of attack is set to zero when the maximum angle of attack subroutine is being used by the predictor.

$$\delta_{DB\ rl}^{*P} = 0$$

However, the maximum angle of attack in the predictor is constrained by the amount of full horizontal stabilizer deflection that the EMS is allowed to use. As for the vehicle, when the pilot selects 75% deflection, the predictor utilizes the maximum attainable angle of attack for this deflection and when the pilot selects full deflection, the predictor only uses full deflection when the angle of attack attainable with this deflection is needed. The gain which constrains the angle of attack to that for 75% deflection in the latter case is computed as,

$$K^P_{\delta H} = q^P/1600 - 0.05\ \dot{H}^{*P}$$

<u>Damping and Constraint Control Loops</u> (Part of subroutine COMX in SDS-930 program, part of COMNDGEN in ALERT program)

The predictor maneuver commands are modulated and limited by control loops to damp out phugoid flight path oscillations and to insure that the vehicle constraints are not exceeded. As mentioned previously, this is done in a constraint control subroutine which is used for both the vehicle and the predictor. Before this subroutine is entered for the predictor, the control loop usage indicator is set to one to indicate that it is going to be used for the predictor.

Since the operation of the control loops is nearly identical for the vehicle and predictor, the operation of them for the predictor was discussed previously while the vehicle command computations were being discussed. Therefore, this discussion will not be repeated here.

After the constraint control computations are completed for the predictor, the predictor bank angle and angle of attack are rate limited to insure that the maximum attitude rates that are imposed on the EMS are not exceeded on any prediction. The computations for this are as follows:

$\phi^P_{prev} = 0$, if predictor previous history indicator is zero

$$\Delta\phi_{max} = \dot{\phi}_{max} \; \Delta t^P$$

$\phi^P = \phi^P_c$ rate limited:

$$\phi^P_{prev} - \Delta\phi_{max} \leq \phi^P_c \leq \phi^P_{prev} + \Delta\phi_{max}$$

$$\phi^P_{prev} = \phi^P$$

$$\alpha^P_{c\,1} = \alpha^P_c \cos \phi^P / \cos \phi^P_c$$

$$\Delta\alpha_{max} = \dot{\alpha}_{max} \; \Delta t^P$$

$\alpha^P = \alpha^P_{c\,1}$ rate limited to:

$$\alpha^P_{prev} - \Delta\alpha_{max} \leq \alpha^P_{c\,1} \leq \alpha^P_{prev} + \Delta\alpha_{max}$$

$$\alpha^P_{prev} = \alpha^P$$

At this point, the computation of the predictor commands is completed. A return is then made to the predictor where the equations of motion are continued.

(3) Prediction Processing and Phasing

After each prediction is completed, the prediction processing and phasing section is entered. In this section, the GAA range coordinates are computed from the integrated portion of the predictions and from closed form for the terminal portions of the predictions. The inputs for the coefficient set up subroutine are then set from the GAA range coordinates and the value of predictor independent variable corresponding to the time at which the respective GAA range prediction was started. The predictor control codes for the next prediction are then set and the programs branch back to the predictor initialization section.

The phasing of the predictor is controlled by the predictor phasing code. As mentioned previously, this code is set to three when the EMS is first initialized. In addition, when the EMS is initialized, the prediction type code is set to minus one, indicating that a maximum range prediction is desired first, and the stopping condition code is set to one indicating that the predictor is to stop when the predictor stopping energy is reached.

When this section is reached, the predictor phasing code is first checked, If it is three, as it will be after the first prediciton, a branch is made to a section where the maximum range GAA coordinate is computed.

$$R^P_{max} = R^P_{final} + (\partial R/\partial E)\ (E^P_{final} - E_{final})$$

The value of the independent variable for this prediction is then set for the coefficient set up subroutine as,

$$I^P_{RX} = I^P$$

In addition, a maximum range prediction ready code is set to one to indicate to the coefficient setup subroutine, when it is entered, that a maximum range prediction is ready to be used.

The predictor phasing code for the next prediction is then set to four. For this prediction, the prediction type code is set to zero, indicating that a minimum range prediction is desired next, and the stopping condition code is set to minus one indicating that the predictor is to stop after a 180° lateral turn has been made. A branch is then made back tc the predictor initialization section.

After a minimum range prediction is completed, this section is again entered. If the predictor phasing code is four, as it will be in this case, a branch is made to a section where the minimum range GAA coodinate is computed and the independent variable and prediction ready code for this prediciton are set for the coefficient setup routine.

$$R^P_{min} = \mu^P_{final}\ k_{nm/rad} - (\partial R/\partial E)\ (E^P_{final} - E_{final})$$

$$I_{RN} = I^P$$

In addition, since the predicted maximum dynamic pressure at pullout is obtained from the minimum range prediction, this quantity is also set here.

$$q^P_{max} = q^P_{max\ final}$$

The predictor phasing code for the next prediction is then set to five, the prediction type code is set to one, indicating that a maximum cross-range prediction is desired next, and the stopping condition code is set to one, indicating that the prediction is to stop when the stopping energy is reached. The stopping energy is also computed here as,

$$E^P_{stop} = E_{final} + k_E \left(E^P_o - E_{final}\right)$$

Again, a branch is made back to the predictor initialization section. After the maximum cross-range prediction is completed, this section is again entered. If the predictor phasing code is five, as it will be in this case, a branch is made to a section where the maximum cross range GAA coordinate is computed and the independent variable and prediction ready code for this prediction are set for the coefficient setup subroutine.

$$R^P_{c\ max} = \left(\lambda^P_{final} - \pi/2\right) k_{nm/rad} + \left(\partial R/\partial E\right) \left(E^P_{final} - E_{final}\right) \sin \xi^P_{final}$$

$$I^P_{Rcx} = I^P$$

The predictor phasing code is then set to three, the prediction type code is set to minus one, indicating that a maximum range prediction is desired next, and the stopping condition code is set to one, indicating that the prediction is to stop when the stopping energy is reached. It should be noted that the predictor control codes now have the same values as they were originally initialized to. As a result of this, the entire procedure just described is started over again. After another maximum range, minimum range, and maximum cross-range predictions are made, the prediction cycle is again started over again. This cyclic prediction of the GAA range coordinates is continued as long as the EMS continues to operate.

(4) Coefficient Set Up (Subroutine COEX15 in SDS 930 program; subroutine COEX in ALERT program)

The coefficient set up subroutine sets up coefficients for the GAA range extrapolators from the predicted ranges and the values of the independent variable corresponding to these ranges. When this subroutine is entered, the prediction ready codes are first checked to determine if any new predictions have been completed since the last time coefficients were set up. If these codes are all zero, the entire coefficient set up procedure is bypassed since there are no new ranges available for setting up coefficients. If any of these codes are one, the coefficients for the corresponding ranges are set up.

In either case, the programs then check to determine if the X-15 engine has either stopped or started firing since the last time that this subroutine was entered. If it has, the engine firing reset code is set to one to indicate that the coefficient set up procedure must be restarted the next time. It is necessary to restart the procedure in this case because the independent variable switches from a combination of energy and time when the engine is firing to time when the engine is not firing. The terminal energy that the pilot has selected is also checked at this point. If it has changed since the last time that this subroutine was entered, the terminal energy reset code is set equal to one. In this case, the "y" intercept coefficients must be reevaluated the next time but the slopes remain the same since only the range reference has shifted.

For the case where the coefficient set up procedure is entered, a check is first made to determine if at least three predictions (maximum range, minimum range, and maximum cross range) have been made. If they have, the GAA status code is set to one to indicate that a GAA is available for generating commands. If less than three predictions have been made, the GAA status code is left at zero to indicate that no GAA is available.

In either case, a check is then made to determine how many predictions of each range (maximum range, minimum range, and maximum cross range) have been made. If only one prediction of any of these ranges has been made since the coefficient set up procedure was started, as is the case when the EMS first starts operating or when this procedure is restarted, then the "y" intercept coefficients for these ranges are set equal to the range and the slope coefficients are set equal to zero. In addition, the previous values of these ranges and the corresponding values of the independent variables are set.

$$R(i)_o = R(i)$$

$$\partial R/\partial I(i) = 0$$

$$R(i)_{prev} = R(i)$$

$$I(i)_{prev} = I(i)$$

If more than one prediction of any of these ranges has been made, then the "y" intercept and slope coefficients for these ranges are evaluated from the current and previous values of these ranges and the corresponding values of the independent variable. The slope coefficients are computed as,

$$\partial R/\partial I(i)_{current} = \frac{R(i) - R(i)_{prev}}{I(i) - I(i)_{prev}}$$

Since the slope coefficients are derivatives, they can become noisy if the errors in the predicted ranges become significant compared to the changes in the ranges between predictions. This can happen when the X-15 is in the glide phase of flight. To prevent this noise from being amplified in the extrapolator, which is a lead device, the slope coefficients are filtered in this case as follows:

$$\partial R/\partial I(i) = \frac{[\partial R/\partial I(i)_{current} + \partial R/\partial I(i)_{prev}]}{2}$$

When the X-15 is in the boost phase of flight, the slope coefficients are set equal to the current values

$$\partial R/\partial I(i) = \partial R/\partial I(i)_{current}$$

In either case, the "y" intercept coefficients are then computed as,

$$R(i)_o = R(i) - \partial R/\partial I(i)\ I(i)$$

The previous values which are necessary are then set as follows:

$$R(i)_{prev} = R(i)$$

$$I(i)_{prev} = I(i)$$

$$\partial R/\partial I(i)_{prev} = \partial R/\partial I(i)$$

After the coefficients have been set up, the prediction ready codes are set back to zero to indicate so and the programs branch back to the section where new inputs are obtained.

E. Vehicle Characteristics Utilized in the EMS

The vehicle characteristics utilized in the EMS are those for X-15 number three with ventral off. The characteristics which are included for this vehicle are the mass, the reference area, the trim aerodynamic lift and drag coefficients, the maximum useable angle of attack, and the angle of attack for maximum lift to drag. The vehicle mass, reference area, and aerodynamic coefficients are utilized in the predictor model of the X-15. The angle of attack data is utilized in generating commands for both the predictor and the vehicle.

1. Aerodynamic Coefficients (Subroutines KACOE1 and KACOE2 in SDS 930 program; subroutines ACO1 and ACO2 in ALERT program)

The aerodynamic coefficients utilized in the EMS are trim coefficients relative to the velocity vector. Trim coefficients are used since the short period effect of the control surfaces on the aerodynamic lift and drag does not have a significant effect on the long period ranges that the predictor predicts and since studies have shown that the pilot can keep the X-15 in a near trim condition for the attitude rates that the EMS commands.

The trim lift and drag coefficients are computed as,

$$C_L = C_{L_\alpha} \alpha$$

$$C_D = C_{D_O} + C_{D_{C_{L^2}}} (C_L)^2 ,$$

where the lift slope coefficient, C_{L_α}, the base drag coefficient, C_{D_O} , and the lift induced drag coefficient, $C_{D_{C_{L^2}}}$, are all functions of Mach number. These computations are made in subroutines KACOE2 and ACO2 in the SDS 930 and

ALERT programs, respectively, and have been referred to previously in this report as,

$$C_L, C_D = f_5 \ (C_{L_\alpha}, C_{D_O}, C_{D_{C_L{}^2}}, \alpha).$$

The coefficients, C_{L_α}, C_{D_O}, and $C_{D_{C_L{}^2}}$, are computed as polynomial functions of Mach number in subroutines KACOE1 and ACO1 in the SDS 930 and ALERT programs, respectively. These polynominal functions have been referred to previously in this report as,

$$C_{L_\alpha}, C_{D_O}, C_{D_{C_L{}^2}} = f_4 \ (M).$$

The manner in which these coefficients vary with Mach number is shown in Figure 8. In the programs, these coefficients are actually computed for the ventral on configuration first since the data that they were reduced from was for this configuration. They are then converted to coefficients for the ventral off configuration before being used in the EMS. The equations used for doing this are as follows:

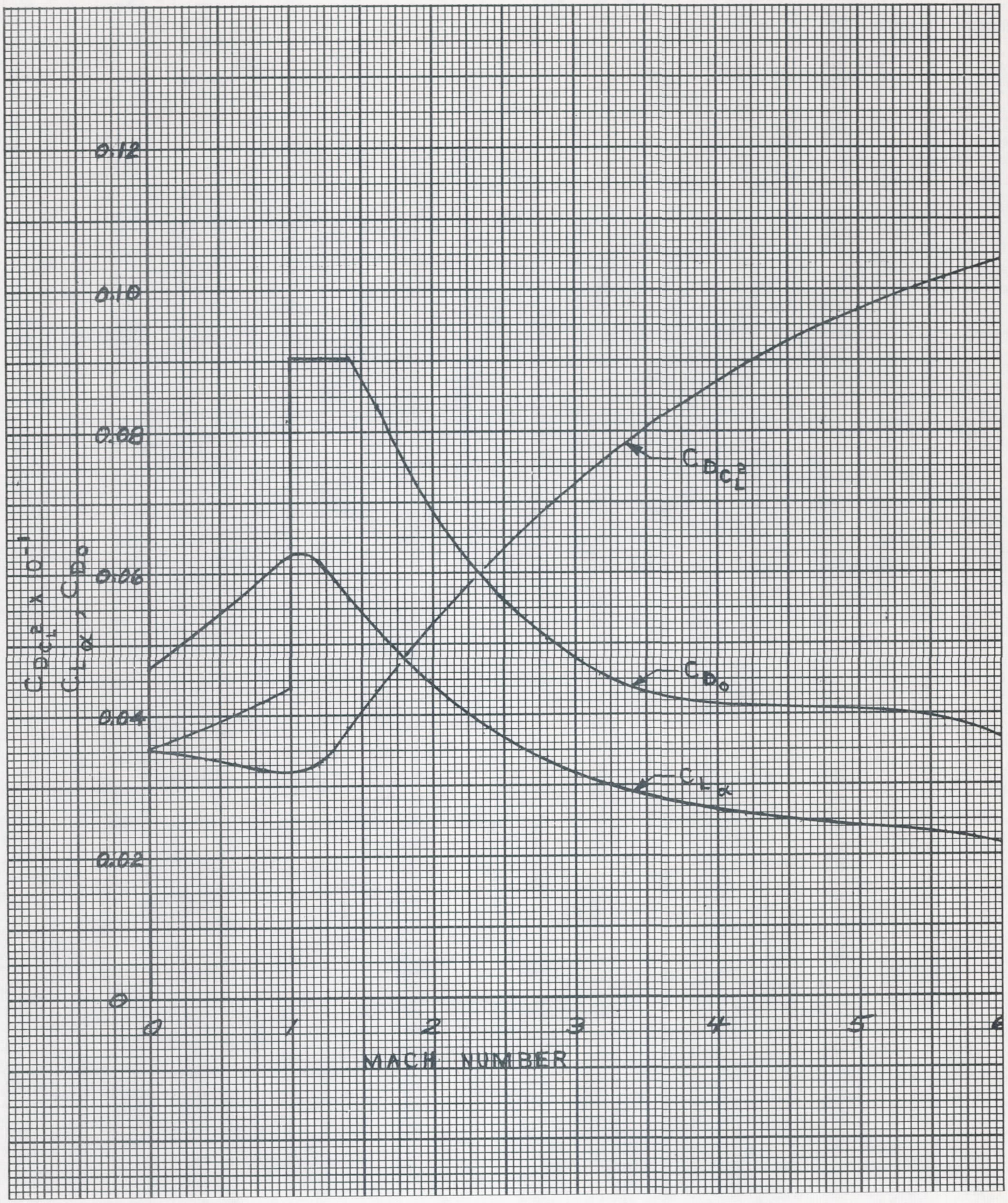


Figure 8.— Aerodynamic data utilized in EMS.

If $M < 1.0$

$$C'_{L_\alpha} = .0464 + .0161M$$

$$C'_{D_O} = .039 + .0095M$$

$$C'_{D_{C_{L^2}}} = .36 - .036M$$

If $1.0 \leq M \leq 1.1$

$$C'_{L_\alpha} = .0464 + .0161M$$

$$C'_{D_O} = .1004$$

$$C'_{D_{C_{L^2}}} = .36 - .036M$$

If $1.1 \leq M \leq 1.5$

$$C'_{L_\alpha} = .1037 - .0451M + .00883M^2 - .000598M^3$$

$$C'_{D_O} = .1004$$

$$C'_{D_{C_{L^2}}} = -.0659 + .382M - .0427M^2 + .00174M^3$$

If $M > 1.5$

$$C'_{L_\alpha} = .1037 - .0451M + .00883M^2 - .000598M^3$$

$$C'_{D_O} = .2127 - .108M + .0233M^2 - .00168M^3$$

$$C'_{D_{C_{L^2}}} = -.0659 + .382M - .0427M^2 + .00174M^3$$

These ventral on coefficients are then converted to ventral off ones as follows.

$$C_{L_\alpha} = 1.003\ C'_{L_\alpha}$$

$$C_{D_0} = .90\ C'_{D_0}$$

$$C_{D_{C_{L^2}}} = .98\ C'_{D_{C_{L^2}}}$$

2. Angle of Attack Data

a. Maximum Useable Angle of Attack (Subroutine KMTIE1 in SDS 930 program, subroutine FMT2 in ALERT program)

The maximum useable angle of attack in the X-15 is limited by the maximum deflection of the horizontal stabilizers at the higher Mach numbers, the lateral stability characteristics of the vehicle at around Mach two, and buffeting near Mach one. In addition, the maximum useable angle of attack is also decreased as the drag brakes are deflected. Therefore, in the EMS, the maximum useable angle of attack is computed as a function of Mach number, drag brake deflection and horizontal stabilizer deflection. This function has been referred to previously in this report as,

$$\alpha_{max} = f_2 \; (M, \; \delta^*_{DB \; rl} \; , \; k_{\delta H}).$$

In the programs, the maximum useable angle of attack for no drag brake deflection at full horizontal stabilizer deflection is first computed as a polynomial function of Mach number. The manner in which this angle of attack varies with Mach number is shown in Figure 9. The polynomial equations used are as follows:

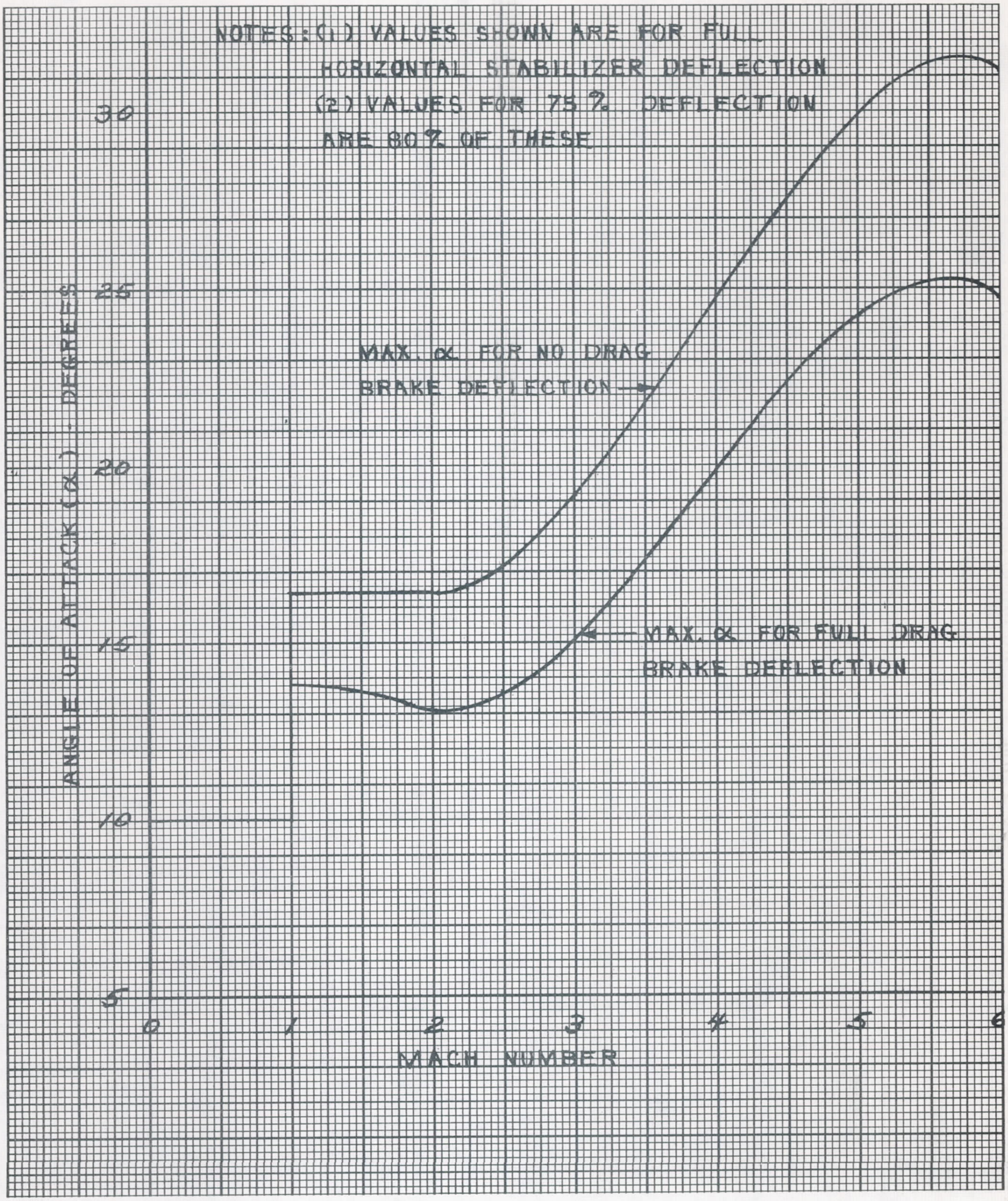


Figure 9.— Maximum useable angle of attack data utilized in EMS.

If $M < 1.1$

$$\alpha_{max\ o} = 10.$$

If $1.1 \leq M \leq 2.0$

$$\alpha_{max\ o} = 16.4$$

If $M > 2.0$

$$\alpha_{max\ o} = 33. - 19.\ M + 6.46\ M^2 - .557\ M^3$$

The increment that this angle of attack is decreased by if the drag brakes are fully deflected is then computed as,

$$\Delta\alpha_{DB\ max} = 0 \qquad , \text{ if } M \leq 1.1$$

$$= 1.7 + .8\ M \qquad , \text{ if } M > 1.1$$

The decrease in the maximum useable angle of attack for any drag brake deflections is assumed to be proportional to the decrease for maximum drag brake deflection. The maximum useable angle of attack for any deflection at full stabilizer deflection is; therefore, computed as,

$$\alpha_{max\ DB} = \alpha_{max\ o} - \delta^{*}_{DB\ rl}\ \Delta\alpha_{DB\ max}$$

The manner in which this angle of attack varies in Mach number is also shown in Figure 9 for the case where the drag brakes are fully deflected.

If the pilot has selected the 75% horizontal stabilizer deflection limit for the EMS, the maximum useable angle of attack for any drag brake deflection at full stabilizer deflection is multiplied by 0.8 since the X-15 can trim about 80% of the maximum trimmable angle of attack at this deflection.

$$\alpha_{max} = .8\ \alpha_{max\ DB}$$

If the pilot has selected the 100% horizontal stabilizer deflection limit for the EMS, the maximum useable angle of attack for any drag brake deflection at full stabilizer deflection is multiplied by a gain, $k_{\delta H}$, which constrains the angle of attack to that for 75% deflection except when maximum deflection is needed.

$$\alpha_{max} = k_{\delta H\ \ell}\ \ \alpha_{max\ DB}$$

where:

$$k_{\delta H\ \ell} = .5 + k_{\delta H} \text{ limited to:}$$

$$.8 \leq (.5 + k_{\delta H}) \leq 1.0$$

b. Angle of Attack for Maximum Lift to Drag (Subroutine KMTIE2 in SDS 930 program; subroutine FMT2 in ALERT program)

In the EMS, the angle of attack for maximum lift to drag is computed as a function of Mach number. This function has been referred to previously in this report as,

$$\alpha_{(L/D)\ max} = f_3\ (M)$$

This function is computed in the programs as follows:

$$\alpha_{(L/D)\ max} = \begin{cases} 6.5 & , \text{ if } M < 1.0 \\ 8.8 & , \text{ if } M \geq 1.0 \end{cases}$$

IV. DESCRIPTION OF EQUATION SYMBOLOGY AND ITS CORRELATION WITH THAT USED IN THE ASSOCIATED COMPUTER PROGRAMS

A list of the symbols used in this report, their description, and their values (if they are constants) is contained in Table 1. In addition, the corresponding symbols used in the SDS 930 and ALERT computer programs are also included in this table to as great an extent as practical. It was not practical to do this in all cases because: (1) certain expressions, which have been assigned engineering symbols in this report, appear as integral parts of larger equations in the computer programs and, therefore, do not have corresponding computer language symbols, (2) some of the fixed point variables in the SDS 930 program have several computer symbols depending on the scaling required (in this case, only the primary symbol is given in Table 1), and (3) some variables have different computer symbols in different subroutines even though they are the same quantity and share the same computer memory location. In addition, in some cases, it will be noted that the same computer symbol is used for two or more different variables. This is because the computer memory location to which such a symbol is assigned is being used as a temporary storage location for several variables; none of which must be saved through a complete cycle.

Although these aspects of computer programming make it impractical to provide a complete list of the corresponding computer program symbols in this report, it is believed that the list provided in Table 1 is sufficient to enable those who are interested in the digital programming aspects of the X-15 EMS to correlate between the programs and the equations presented in this report. To further aid the reader in interpreting the information presented in Table 1, the following notes, which are used in this table, are defined here.

Notes: (1) This symbol is not used in the SDS 930 program

(2) This symbol is not used in the ALERT program

(3) This symbol does not appear as a separate quantity in this program

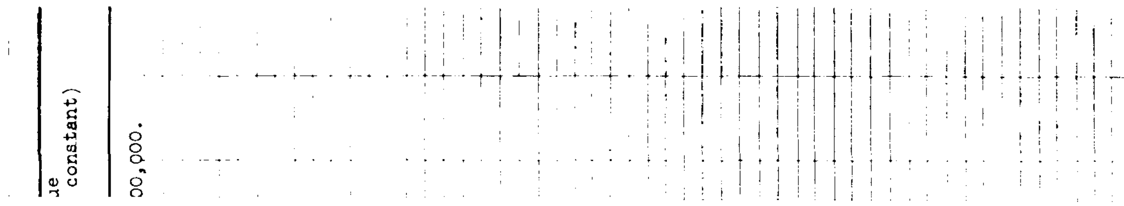
In addition to the variables required in the EMS equations, several codes and indexes are required to cycle the EMS through the separate computational branches discussed previously. A description of these codes, including the symbols used for them in the computer programs is contained in Table 2.

TABLE 1 - LIST OF SYMBOLS

Symbols: Engineering	Symbols: SDS 930	Symbols: Alert	Description	Value (if constant)
$(A_{N\,max}/g_o)$	GL	GLIM	Normal acceleration limit - "g"	5.0
A_N^A	AZV	(2)	Normal acceleration obtained from X-15 analog simulation - ft/sec^2	
A_N^S	(1)	AZI	Normal acceleration obtained from "z" body axis accelerometer in X-15-ft/sec^2	
A_N^V	AZV	COMY	Filtered normal acceleration - ft/sec^2	
(A_N^V/g_o)	GSTRV	GSTV	Filtered normal acceleration - "g's"	
$A^*_{N\,max}$	KGSLE3	KLGS	Nondimensional normal acceleration limit in predictor	1.0
A_N^{*P}	KGSE3	GSTR	Nondimensional normal acceleration in predictor	
$(\partial A_N^V/\partial\alpha)/g_o$	GSTRX	GSTX	Partial of normal acceleration with respect to angle of attack - "g's"/degree	
$(\partial A_N^{*P}/\partial\alpha)$	KGSE4	GSTR	Partial of nondimensional normal acceleration in predictor with respect to angle of attack - 1/degree	
$b_{\Delta R^*}$	KBRBS	BRBS	Value of nondimensional GAA radial error at which angle of attack maneuver command starts to become greater than the minimum value.	
$C_{D_{C_L^2}}$	KCDDE3	NDRG	Lift induced drag coefficient	
C_{D_o}	KCDOE4	PRDR	Zero lift drag coefficient	
C_{L_α}	KCLAE4	PRLF	Lift coefficient slope - 1/degree	
C_D^P	KCDE4	DRAG	Drag coefficient in predictor	
$C^P_{D_{prev}}$	KCDE4	CDP	Drag coefficient in predictor based on previous angle of attack	
C_L^P	KCLE4	LIFT	Lift coefficient in predictor	
$C^P_{L_{prev}}$	KCLE3	CLP	Lift coefficient in predictor based on previous angle of attack	
$C^P_{N_\alpha}$	KCNAE4	CNAP	Normal coefficient slope in predictor - 1/degree	
$C^V_{N_\alpha}$	CNAV	CNAV	Normal coefficinet slope - 1/degree	
$(D/m)^P$	KDME2	DMP	Drag acceleration in predictor - ft/sec^2	
E	EVEH	ENRV	Energy per unit mass - ft^2/sec^2	
E_{final}	EPF7	ENRD	Terminal energy corresponding to desired altitude and velocity on approach to selected landing site - ft^2/sec^2	

TABLE 1 (CONT.)

Symbol: Engineering	SDS 930	Alert	Description	Value (if constant)
$E_{HK}(i)$	EPFHK(i)	KEHI(i)	High key terminal energies for individual lake beds - ft^2/sec^2	3,560,000.
$E_{LK}(i)$	EPFLK(i)	KELI(i)	Low key terminal energies for individual lake beds - ft^2/sec^2	500,000.
E_{stop}	EFLAG	(3)	Energy at which EMS stops operating - ft^2/sec^2	
E^P	KED1	ENRP	Energy in predictor - ft^2/sec^2	
E^P_{final}	E	(3)	Value of energy in predictor at the end of a prediction - ft^2/sec^2	
E^P_o	EINIT	EINT	Initial condition value of energy in predictor	
E^P_{stop}	KEPSK1	EPS	Energy stopping condition in predictor	
g_o	G7	KG7	Gravitational acceleration at sea level - ft/sec^2	32.17
H^*	KHXE2	HDST	Nondimensional damping parameter input to constraint control loops	
$\dot{H}^*_c$	KHSRE2	HDSV	Filtered and shaped damping parameter in constraint control loops	
$\dot{H}^*_f$	KHSRE2	HDSV	Filtered damping parameter in constraint control loops	
$\dot{H}^*_{lim}$	KHDLE2	KHDT	Maximum value of damping parameter which is filtered in constraint control loops	2.0
$\dot{H}^{*P}$	KHDSE2	KDSP	Nondimensional damping parameter in predictor	
$\dot{H}^{*V}$	HDTVB	HDSV	Nondimensional damping parameter for vehicle	
$\Delta\dot{H}^*$	KCME2	COM1	Difference between damping parameter and maximum value which is filtered	
$\Delta\dot{H}^*_{bypass}$	KCME2	COM1	Increment in damping parameter which bypasses filter	
$\Delta\dot{H}^*_f$	KHYE2	HDOW	Filtered damping parameter increment	
$\Delta\dot{H}^*_{f\ input}$	KHINE2	HKIW	Damping parameter increment input to filter	
$\Delta\dot{H}^*_{f\ prev}$	KHYPE2	HDOT	Previous value of damping parameter output of filter	
$\Delta\dot{H}^*_{prev}$	KHXPE2	HDIT	Previous value of damping parameter input to filter	
$\Delta\dot{H}^{*P}_{f\ prev}$	KYPPE2	HDOP	Previous predictor value of output of damping filter	
$\Delta\dot{H}^{*P}_{prev}$	KXPPE2	HDIP	Previous predictor value of input to damping filter	
$\Delta\dot{H}^{*v}_{prev}$	KYVPE2	HDOV	Previous vehicle value of output of damping filter	
$\Delta\dot{H}^{*v}_{prev}$	KXVPE2	HDIV	Previous vehicle value of input to damping filter	
$h_{q\ lim}$	KX27	KHX2	Altitude above which it is assumed that sensed dynamic pressure is not reliable - ft	180,000.



V. REFERENCES

1. Anon.: An Energy Management System Design for Flight Testing in the X-15. Rept. No. 7176-935001, Bell Aerosystems Company, April 1963.

2. Cockayne, William G.: Program Manual on X-15 EMS Computer Programs for the SDS 930 Computer. Rept. No. 7237-927001, Bell Aerosystems Company, March 1966.

TABLE 1 (CONT.)

Symbol			Description	Value (if constant)
Engineering	SDS 930	Alert		
$E_{HK}(i)$	EPFHK(i)	KEH1(i)	High key terminal energies for individual lake beds - ft^2/sec^2	3,560,000.
$E_{LK}(i)$	EPFLK(i)	KEL1(i)	Low key terminal energies for individual lake beds - ft^2/sec^2	500,000.
E_{stop}	EFLAG	(3)	Energy at which EMS stops operating - ft^2/sec^2	
E^P	KED1	ENRP	Energy in predictor - ft^2/sec^2	
E^P_{final}	E	(3)	Value of energy in predictor at the end of a prediction - ft^2/sec^2	
E^P_o	EINIT	EINT	Initial condition value of energy in predictor	
E^P_{stop}	KEPSK1	EPS	Energy stopping condition in predictor	
g_o	G7	KG7	Gravitational acceleration at sea level - ft/sec^2	32.17
$\dot{H}^*$	KHXE2	HDST	Nondimensional damping parameter input to constraint control loops	
$\dot{H}^*_c$	KHSRE2	HDSV	Filtered and shaped damping parameter in constraint control loops	
$\dot{H}^*_f$	KHSRE2	HDSV	Filtered damping parameter in constraint control loops	
$\dot{H}^*_{lim}$	KHDLE2	KHDT	Maximum value of damping parameter which is filtered in constraint control loops	2.0
$\dot{H}^{*P}$	KHDSE2	KDSP	Nondimensional damping parameter in predictor	
$\dot{H}^{*V}$	HDTVB	HDSV	Nondimensional damping parameter for vehicle	
$\Delta\dot{H}^*$	KCME2	COM1	Difference between damping parameter and maximum value which is filtered	
$\Delta\dot{H}^*_{bypass}$	KCME2	COM1	Increment in damping parameter which bypasses filter	
$\Delta\dot{H}^*_f$	KHYE2	HDOW	Filtered damping parameter increment	
$\Delta\dot{H}^*_{f\,input}$	KHINE2	HKIW	Damping parameter increment input to filter	
$\Delta\dot{H}^*_{f\,prev}$	KHYPE2	HDOT	Previous value of damping parameter output of filter	
$\Delta\dot{H}^*_{prev}$	KHXPE2	HDIT	Previous value of damping parameter input to filter	
$\Delta\dot{H}^{*P}_{f\,prev}$	KYPPE2	HDOP	Previous predictor value of output of damping filter	
$\Delta\dot{H}^{*P}_{prev}$	KXPPE2	HDIP	Previous predictor value of input to damping filter	
$\Delta\dot{H}^{*V}_{prev}$	KYVPE2	HDOV	Previous vehicle value of output of damping filter	
$\Delta\dot{H}^{*V}_{prev}$	KXVPE2	HDIV	Previous vehicle value of input to damping filter	
$h_{q\,lim}$	KX27	KHX2	Altitude above which it is assumed that sensed dynamic pressure is not reliable - ft	180,000.

TABLE 1 (CONT.)

Symbol			Description	Value (if constant)
Engineering	SDS 930	Alert		
h_{top}	HTOP	KTOP	Assumed top of the appreciable atmosphere - ft	200,000.
h^A	HV	(2)	Altitude obtained from analog simulation of X-15 - ft	
h^I	(1)	ALTI	Altitude obtained from navigational computations in VERDAN computer - ft	
h^P	KALT	ALTP	Altitude in predictor - ft	
h_o^P	ALTINT	ALIN	Initial condition value for altitude in predictor - ft	
h_{prev}^P	KALTO	ALTO	Previous value of altitude in predictor	
h^v	HVEH	ALTV	Altitude of vehicle (either h^A or h^I) - ft.	
$h_{\bullet}^v$	HR	ALTR	Density altitude of vehicle - ft	
$\dot{h}^A$	HDV	(2)	Altitude rate obtained from analog simulation of X-15 - ft/sec	
$\dot{h}^I$	(1)	VVI	Altitude rate obtained from navigational computations in VERDAN computer - ft/sec	
$\dot{h}^P$	KHD	DALT	Altitude rate in predictor - ft/sec	
$\dot{h}_{prev}^P$	KHDP	DALR	Previous value of altitude rate in predictor - ft/sec	
$\dot{h}^v$	DHVEH	DALV	Altitude rate of vehicle (either $\dot{h}^A$ or $\dot{h}^I$) - ft/sec	
$\dot{h}_{eq}^v$	HDEQV	DHEV	Equilibrium altitude rate for vehicle - ft/sec	
Δh^P	KDH	DELH	Change in altitude in predictor between integration steps - ft	
I_{RCX}	XRCX(1)	XR1C	Initial condition value for independent variable on cross range prediction	
I_{RN}	XRN(1)	XR1N	Initial condition value for independent variable on maximum range prediction	
I_{RX}	XRX (1)	XR1X	Initial condition value for independent variable on minimum range prediction	
$I(i)$	XRX(1)	XR1	Initial condition values for independent variable on predictions - sec	
$I(i)_{prev}$	XRX(2)	XR2	Previous value of initial condition values of independent variable - sec	
I^P	XEXTI	XEXI	Independent variable in predictor - sec	
I^v	XEXT	XEXT	Independent variable for vehicle - sec	
ΔI_{off}^P	EPI	EPI	Energy increment which is subtracted from predictor independent variable when X-15 engine is off - sec	
ΔI_{off}^v	EPV	EPV	Energy increment which is subtracted from vehicle independent variable when X-15 engine is off - sec	

TABLE 1 (CONT.)

Symbol: Engineering	SDS 930	Alert	Description	Value (if constant)
ΔI_{on}^{v}	EXV	EXV	Energy component of vehicle independent variable when X-15 engine is on - sec	
k_E	RNFF7	KRNF	Constant used in computing stopping energy for predictor	.05
$k_{\dot{H}^*}$	KHDFD2	DHFP	Constant used in computing nondimensional damping parameter - ft^2/sec^2	700,000.
$k_{R_c^*/\Delta R^*}$	KPRSE2	DRSD	Gain term used to increase gain on increment in bank angle command due to cross range errors as landing site moves aft in GAA	
$k_{\Delta R^*}$	KGRBS	GRBS	Gain term which controls sensitivity of EMS angle of attack command to changes in position of landing site in GAA	
k_t	AKT7	KTIM	Gain term on time component of independent variable	20,000.
$k_{\Delta t}$	KVME2	VOM	Velocity dependent gain term on integration interval in predictor - ft/sec	
$k_{\Delta t\ o}$	KVB7	KVBN	Maximum value of gain term on integration interval in predictor - ft/sec	640.
$k_{\ddot{x}}$	KDCNE1	DCON	Gain on second derivative terms in predictor integration routine	
$k_{\alpha/\dot{H}^*}$	K107E1	K10	Gain on damping modulation on angle of attack - degrees	3.
k_{α/q^*}	K77	K7	Gain on dynamic pressure modulation on lower angle of attack limit - degrees	150.
$k_{\alpha/\dot{H}^*}$	K47E1	K4	Gain on damping modulation on maximum bank angle limit - degrees	6.
$k_{\phi\ lim}$	KX27E1	KXI2	Gain on GAA polar angle limit on bank angle maneuver command	0.6
k_{ϕ/q^*}	K67D2	K6	Gain on dynamic pressure modulation on maximum bank angle limit - degree	1100.
k_{ϕ/R_c^*}	K17	K1	Gain on component of bank angle command due to cross range errors - degrees	70.
$k_{\phi/\ R^*}$	K27E1	K2	Gain on component of bank angle command due to range errors - degrees	9.
$k_{\delta H}^{P}$	KSTABD	SDTR	Gain on horizontal stabilizer deflection in predictor	
k_{ϕ}^{P}	KPH7E1	KPHI	Gain on bank angle maneuver command in predictor	0.6
$k_{\delta H}^{v}$	KSTABD	SDTR	Gain on horizontal stabilizer deflection for vehicle	
$(L/m)^{P}$	KLME1	LMP	Lift acceleration in predictor - ft/sec^2	
$(L/m)_{v}^{P}$	KCLPE4	GSTE	Vertical component of lift acceleration in predictor - ft/sec^2	
$(L/m)_{v}^{P}$	KGSAE4	GSTA	Limited vertical component of lift acceleration in predictor - ft/sec^2	
$(L/m)_{v1\ prev}^{P}$	KGSPE4	GSPR	Previous value of limited vertical component of lift acceleration - ft/sec^2	
$(L/m)_{v}^{P}$	KCAE2	COMA	Rate of change of limited vertical component of lift acceleration - ft/sec^2/sec	
$(L/m)_{v1}^{P}$	KCAE2	COMB	Limited value of rate of change of vertical component of lift acceleration - ft/sec^2/sec	

TABLE 1 (CONT.)

Symbol			Description	Value (if constant)
Engineering	SDS 930	Alert		
$(\dot{L}/m)_v^{*P}$	(3)	(3)	Nondimensional rate of change of vertical component of lift acceleration - 1/sec	
M	KTME2	MACT	Mach number input to constraint control section	
M_{lim}	KMLE2	KMKL	Constant value of Mach number used in setting gain on second derivative terms in predictor integration routine	1.1
$M_{q\ lim}$	AMX27	KMX2	Mach number below which sensed dynamic pressure is assumed to be unreliable	2.5
M^P	KME2	MACP	Mach number in predictor	
M^V	AMCVEH	MACV	Mach number of vehicle	
m	AMASS7	KMAS	Vehicle mass (empty) - slugs	467.
P_T^S	(1)	PTI	Sensed impact pressure on X-15	
q	KQ	QT	Dynamic pressure input to constraint control loops - lb/ft^2	
q_{lim}	QMNV7	KQMN	Minimum value of sensed dynamic pressure that is assumed to be reliable - lb/ft^2	50.
$q_{\phi\ lim}$	KQNV7	KQNM	Value of dynamic pressure below which it is assumed that aerodynamic sufaces on X-15 are not effective for roll control - lb/ft^2	50.
q^P	KQ	QPRE	Dynamic pressure in predictor - lb/ft^2	
$q^P_{max\ final}$	KQSPE3	QSPM	Predicted dynamic pressure at pullout - lb/ft^2	
q^V	QCV	QCV	Dynamic pressure on vehicle (either sensed or computed) lb/ft^2	
q^{VS}	QVEH	QVEH	Sensed dynamic pressure on vehicle - lb/ft^2	
$\sqrt{q^A}$	QOV	(2)	Square root of dynamic pressure obtained from analog simulation of X-15	
$(q\ S/m)^P$	KQSOM	QSOM	Dynamic pressure force per unit mass - lb/slug	
q^*	KQSE3	QSTT	Nondimensional dynamic pressure input to constraint control section	
q_c^*	KQSDE3	QSD	Maximum of current or predicted dynamic pressure for vehicle	
$q^*_{c\ mod}$	(3)	(3)	Damping modulated nondimensional dynamic pressure term	
q^*_{lim}	KQL7E3	KLQS	Nondimensional dynamic pressure limit	0.8
q^{*P}_{max}	KQSPE3	QSPM	Predicted nondimensional dynamic pressure at pullout	
Δq_c^*	KS12E5	S12T	Shaped increment of dynamic pressure in excess of limit	
Δq^*_{lead}	(3)	(3)	Nondimensional dynamic pressure lead term due to damping	

TABLE 1 (CONT.)

Symbol			Description	Value (if constant)
Engineering	SDS 930	Alert		
R_c	RC(1)	RC	Cross range to go to landing site - nm	
$R_{c\ max}$	RCXEX	RCMX	Extrapolated maximum cross range capability of X-15 - nm	
$R_{c\ max\ o}$	CRCX(1)	CRC	The "y" intercept coefficient used in entrapolating cross range - nm	
R(i)	RX(1)	R	Current values of predicted ranges in coefficient set up subroutine - nm	
$R(i)_o$	CRX(1)	CR	The "y" intercept coefficients used in entrapolating ranges - nm	
$R(i)_{prev}$	RX(2)	RPR	Previous values of predicted ranges in coefficient set up subroutine - nm	
R_{max}	RXEX	RMAX	Extrapolated maximum range capability of X-15 - nm	
$R_{max\ o}$	CRX(1)	CRX	The "y" intercept coefficient used in extrapolating maximum range - nm	
R_{min}	RNEX	RMIN	Extrapolated minimum range capability of X-15 - nm	
$R_{min\ o}$	CRN(1)	CRN	The "y" intercept coefficient used in extrapolating minimum range - nm	
R_{nom}	RNOM	RNOM	Range to the geometric center of the GAA - nm	
R_{TG}	RTG(1)	RTG	Range to go to the landing site - nm	
R^P	KRE3	RPRE	Range in the predictor - nm	
$R^P_{c\ max}$	RCMAX(1)	RCMX	Predicted maximum cross range capability of X-15 - nm	
R^P_{final}	RANGE(1)	(3)	Final value of predictor range at the end of a prediction - nm	
R^P_{max}	RMAX(1)	RMAX	Predicted maximum range capability of the X-15 - nm	
R^P_{min}	RMIN(1)	RMIN	Predicted minimum range capability of the X-15 - nm	
R^*_c	RCSTR	RCST	Nondimensional cross range position of landing site in GAA	
R^*_{cf}	RCSTR	RCST	Filtered value of R^*_c	
$R^*_{c\ lim}$	KONE	CONE	Value of R^*_c at laterally boundary of bank reversal zone	
$R^*_{c\ prev}$	RCSTRP	RCSR	Previous value of filtered R^*_c	
$\bar{R}$	RBAR	RBAR	Straight line range to go to landing site - nm	
$\dot{R}^P$	KRDE3	DRP	Range rate in predictor - nm/sec	
$\dot{R}^P_{prev}$	DRDPE3	DRPR	Previous value of predictor range rate - nm/sec	
ΔR	DR	DR	Range increment between range to go and nominal range - nm	
$\Delta R_{TG\ DZ}$	B(4)	RTGD	Dead zone increment in range to go - nm	

TABLE 1 (CONT.)

Symbol: Engineering	SDS 930	Alert	Description	Value (if constant)
ΔR^*	DRSTG	DRSG	Nondimensional range position of landing site in GAA	
ΔR_B^*	DRSTR	DRS	Nondimensional range error signal used to generate maneuver commands	
ΔR_{Bf}^*	DRSTR	DRS	Filtered value of ΔR_B^*	
$\Delta R^*_{B\ lim}$	KRSLE2	KDRS	Value of ΔR_B^* at fore boundary of bank reversal zone	0.8
$\Delta R^*_{B\ prev}$	DRSTRP	DRPR	Previous value of filtered ΔR_B^*	
ΔR_f^*	DRSTG	DRSG	Filtered value of ΔR^*	
ΔR^*_{prev}	DRSTGP	DRGP	Previous value of filtered ΔR^*	
$\Delta \bar{R}^*$	RBSTR	RBST	Nondimensional radial error signal used to generate maneuver commands	
$\Delta \bar{R}_f^*$	RBSTR	RBST	Filtered value of $\Delta \bar{R}^*$	
$\Delta \bar{R}^*_{prev}$	RBSTP	RBSP	Previous value of filtered $\Delta \bar{R}^*$	
$\partial R/\partial E$	PRE27	KRE1	Partial of range with respect ot energy on a maximum L/D flight at about Mach one - $nm/ft^2/sec^2$	
$\partial R/\partial I(i)$	CR(2)	CR1	Slope coefficients used in extrapolating range capabilities - nm/sec	
$\partial R/\partial I(i)_{prev}$	CR2P	CR2	Previous values of slope coefficients	
$\partial R_{c\ max}/\partial I$	CRCX(2)	CR1C	Slope coefficient used in extrapolating maximum cross range - nm/sec	
$\partial R_{max}/\partial I$	CRX(2)	CR1X	Slope coefficient used in extrapolating maximum range - nm/sec	
$\partial R_{min}/\partial I$	CRN(2)	CR1N	Slope coefficient used in extrapolating minimum range - nm/sec	
r_e	RAD7	KRAD	Radius of the earth at sea level - ft	20.93×10^6
S	S7	KS7	Reference area of the X-15 - ft^2	200.
t^P	KTE2	TIMP	Time in predictor - sec	
t^v	TVEH	TIMO	Vehicle flight time - sec	
t^v_{prev}	TVP	TIPR	Vehicle flight time on previous update of commands - sec	
Δt	KDTXE2	DTMT	Time between updates in constraint control section - sec	
Δt^P	KDTE2	DTMP	Integration interval in predictor - sec	
Δt^P_{prev}	KDTPE2	DTPR	Previous value of predictor integration interval - sec	
Δt^v	DTV	DTMV	Time between updates of vehicle commands - sec	
V_s	VS	VS	Velocity of sound - ft/sec	

TABLE 1 (CONT.)

Symbol: Engineering	SDS 930	Alert	Description	Value (if constant)
V^P	KVPE3	VELP	Velocity in predictor - ft/sec	
V^P_o	VELINT	VLIN	Initial condition value of predictor velocity - ft/sec	
V^v	VVEH	VELV	Velocity of vehicle - ft/sec	
V^v_H	VVH	VLHV	Horizontal component of vehicle velocity -	
$(V^v_H)^2$	VVHSQ	(2)	Square of V^v_H - ft^2/sec^2	
$\dot{V}^P$	KVDE2	DVEL	Velocity rate in predictor - ft/sec/sec	
$\dot{V}^P_{prev}$	KVDPE2	DVLR	Previous value of predictor velocity rate - ft/sec/sec	
X^A	XEA	(2)	Cross range position of vehicle obtained from analog simulation of X-15 - ft	
X^v	XE	(2)	East-west position of X-15 - ft	
$\dot{X}^A$	XEDA	(2)	Cross range component of vehicle velocity obtained from analog simulation of X-15 - ft/sec	
$\dot{X}^I$	(1)	VEI	East-west component of vehicle velocity obtained from VERDAN navigational computations - ft/sec	
$\dot{X}^v$	XED	(2)	East-west component of X-15 velocity - ft/sec	
Y^A	YEA	(2)	Range position of vehicle obtained from analog simulation of X-15 - ft	
Y^v	YE	(2)	North-south position of X-15 - ft	
$\dot{Y}^A$	YEDA	(2)	Range component of vehicle velocity obtained from analog simulation of X-15 - ft/sec	
$\dot{Y}^I$	(I)	VNI	North-south component of vehicle velocity obtained from VERDAN navigational computations - ft/sec	
$\dot{Y}^v$	YED	(2)	North-south component of X-15 velocity - ft/sec	
α_{BS}	KS21E1	S21T	Angle of attack maneuver command on back side of L/D curve - degree	
$\alpha_{BS\,1}$	KABSE1	SABS	Limited valueof α_{BS} - degree	
$\alpha_{(L/D)\,max}$	KS18E1	S18T	Angle of attack for maximum lift to drag ratio - degrees	
$\alpha_{lim/q}$	KS20E1	S20T	Dynamic pressure modulated lower limit on angle of attack - degree	
α_{max}	KS17E1	S17T	Maximum useable angle of attack - degrees	
α_{mc}	KS22E1	S22T	Angle of attack maneuver command for vehicle - degrees	
α_{min}	KALNE1	KAFD	Minimum allowable angle of attack - degree	

TABLE 1 (CONT.)

Symbol: Engineering	Symbol: SDS 930	Symbol: Alert	Description	Value (if constant)
α_{q1}	KS23E1	S23T	Angle of attack command after dynamic pressure limiting - degrees	
$\alpha_{(q1 + \dot{H}^*)}$	KS26E1	S27T	Angle of attack command after dynamic pressure limiting and damping modulation - degrees	
$\alpha_{(q1 + \dot{H}^* + 1)}$	KALFE1	AFOT	Angle of attack command after dynamic pressure limiting/damping modulation, and α_{max} limiting - degrees	
α^A	ALFV	(2)	Angle of attack obtained from analog simulation of X-15 - degrees	
α^P	KALFE1	ALFP	Final rate limited angle of attack in predictor - degrees	
α^P_c	KALFE1	ALFP	Angle of attack command in predictor prior to rate limiting - degrees	
α^P_{mc}	KS22E1	S22T	Angle of attack maneuver command in predictor - degrees	
α^P_{prev}	KALPE1	ALPR	Previous value of α^P - degrees	
α^S	(2)	ALFI	Sensed angle of attack obtained from "Q" ball in X-15 - degrees	
α^V	AVEH	ALFV	Angle of attack of vehicle - degrees	
α^V_c	AL	ALFC	Angle of attack command for vehicle prior to rate limiting - degrees	
$\alpha^V_{c\ prev}$	ALP	ALPR	Previous value of rate limited vehicle angle of attack command - degrees	
α^V_c	AL	ALFC	Final rate limited angle of attack command for vehicle - degrees	
$\cos \alpha^V$	CALF	CAFV	Cosine of vehicle angle of attack	
$\sin \alpha^V$	SALF	SAFV	Sine of vehicle angle of attack	
$\dot{\alpha}_{max}$	ALRL7	1/KALD	Maximum rate of change of angle of attack - degrees/sec	4.0
$\Delta\alpha_{FS}$	KDALE1	DALF	Increment in angle of attack maneuver command on the front side of the L/D curve - degrees	
$\Delta\alpha_{lim/q}$	KCME1	COM1	Increment in lower angle of attack limit due to dynamic pressure modulation - degrees	
$\Delta\alpha_{max}$	DALX	DALF	Maximum change in angle of attack command that rate limit will allow between updates - degrees	
$\bar{\beta}$	B7	KBET	Average value of density decay parameter used to compute damping parameter - 1/ft	4.6×10^{-15}
β^V	BETV	BETV	Density decay parameter used to compute density for the vehicle - 1/ft	
β^P	KBE7	BETP	Local density decay parameter in the predictor - 1/ft	
γ^P	KGME5	GAMP	Flight path angle in the predictor - radians	

TABLE 1 (CONT.)

Symbol: Engineering	Symbol: SDS 930	Symbol: Alert	Description	Value (if constant)
γ_o^P	GAMINT	GMIN	Initial condition value of predictor flight path angle - radians	
γ^v	GVEH	GAMV	Flight path angle of vehicle - radians	
$\cos \gamma^P$	KCGE3	CGMP	Cosine of γ^P	
$\sin \gamma^P$	KSGE3	SGMP	Sine of γ^P	
$\dot{\gamma}^P$	KGDE5	DGAM	Rate of change of flight path angle in predictor - radians/sec	
$\dot{\gamma}^P_{prev}$	KGDPE5	DGMR	Previous value of predictor flight path angle rate - radians/sec	
$\delta_{DB\ max}$	(3)	(3)	Maximum deflection of X-15 drag brakes - degrees	35.
$\delta^v_{DB\ c}$	VDBDC	IDBQ	Final drag brake deflection command for vehicle - degrees	
$\delta^*_{DB\ DZ}$	DBDB	DBDB	Drag brake command dead zone - percent of max	
$\delta^*_{DB\ max}$	NCHK	NCHK	Maximum drag brake deflection indicator - percent of max	
$\delta^*_{DB\ rl}$	IDB	IDB	Rate limited position of drag brakes used in constraint control section - percent of max	
$\delta^{*P}_{DB\ rl}$	IPDB	IPDB	Rate limited position of predictor drag brakes - percent of max	
δ^*_{DB}	DBD	VDBD	Position of vehicle drag brakes obtained from discrete deflection indicator - percent of max	
$\delta^*_{DB\ c}$	VDBDC	VDBC	Drag brake deflection command for vehicle - percent of max	
$\delta^*_{DB\ lim}$	DBL	DBL	Constraint limit on drag maneuver command - percent of max	
$\delta^{*v}_{DB\ lim/\dot{H}^*}$	DBLHDS	DBLH	Damping limit on drag brake maneuver command - percent of max	
$\delta^{*v}_{DB\ lim/M}$	DBLM	DBLM	Mach number limit on drag brake maneuver command percent of max	
$\delta^{*v}_{DB\ lim/q}$	DBLQ	DBLQ	Dynamic pressure limit on drag brake maneuver command - percent of max	
$\delta^{*v}_{DB\ mc}$	VDBDC	VDBC	Drag brake deflection maneuver command - percent of max	
$\delta^{*v}_{DB\ prev}$	DBDP	VDBP	Previous value of rate limited position of vehicle drag brakes - percent of max	
$\delta^{*v}_{DB\ rl}$	DBDO	VDBO	Rate limited position of vehicle drag brakes - percent of max	
$\delta^{*v}_{DB/\Delta R^*_B}$	VDBDC	VDBB	Component of drag brake maneuver command due to range error signal - percent max	
$\delta^{*v}_{DB/\Delta R^*}$	VDBCA	VDBA	Component of drag brake maneuver command due to radial error signal - percent of max	

TABLE 1 (CONT.)

Symbol			Description	Value (if constant)
Engineering	SDS 930	Alert		
$\Delta\delta^{*v}_{DB}$	DDBD	VDDB	Maximum change in vehicle drag brake position allowed by rate limit between updates - percent of max	
θ_{GAA}	KPBRE1	PBR	Polar angle coordinate of landing site in GAA - degrees	
$\cos\theta^{v}$	CTHT	CTHT	Sine of vehicle pitch angle	
$\sin\theta^{v}$	STHT	STHT	Cosine of vehicle pitch angle	
λ_o	ALATI	KCLT	Co latitude of Edwards beacon - radians	
λ^D	AMT7	CLTD	Co latitude of landing site selected by pilot - radians	
$\lambda^D(i)$	AMTHK(i)	CLH1(i	Co latitudes of landing sites - radians	
λ^P	KLEG	CLTP	Co latitude in predictor - radians	
λ^P_{final}	ALAM(1)	(3)	Final value of predictor co latitude at end of prediction - radians	
λ^v	ALATV	CLTV	Co latitude of vehicle - radians	
$\dot{\lambda}^P$	KLDE7	DCLT	Rate of change of co latitude in predictor - radians/sec	
$\dot{\lambda}^P_{prev}$	KLDPE7	DCLR	Previous value of predictor co latitude rate - radians/sec	
$\Delta\lambda^D$	DLAM1	DLTD	Increment in co latitude between X-15 and landing site - radians	
$\Delta\lambda^I$	(1)	LATI	Increment in co latitude, between X-15 and Edwards beacon, obtained from VERDAN navigational computations	
$\Delta\lambda^v$	DLATV	(2)	Increment in co latitude between X-15 and Edwards beacon - radians	
μ_o	ALONGI	KLNG	Longitude of Edwards beacon - radians	
μ^D	PMUT7	LNGD	Longitude of landing site selected by pilot - radians	
$\mu^D(i)$	PMUTHK(i)	LGH1(i	Longitudes of landing sites - radians	
μ^P	KME6	LNGP	Longitude in predictor - radians	
μ^P_{final}	AMU(1)	(3)	Final value of predictor longitude at end of prediction - radians	
μ^v	ALONGV	LNGV	Longitude of vehicle - radians	
$\dot{\mu}^P$	KMDE7	KLNG	Rate of change of longitude in predictor - radians/sec	
$\dot{\mu}^P_{prev}$	KMDPE7	DLGR	Previous value of predictor longitude rate - radians/sec	
$\Delta\mu^D$	DMEW1	DLGD	Increment in longitude between X-15 and landing site - radians	
$\Delta\mu^I$	(1)	LNGI	Increment in longitude, between X-15 and Edwards beacon, obtained from VERDAN navigational computations - radians	

TABLE 1 (CONT.)

Symbol: Engineering	SDS 930	Alert	Description	Value (if constant)
$\Delta\lambda^V$	DLONGV	(2)	Increment in longitude between X-15 and Edwards beacon - radians	
ξ^P	KXIE5	XIP	Heading angle in predictor - radians	
ξ^P_{final}	XI(1)	(3)	Final value	
$\cos\ \xi^P$	KCXIE3	CXIP	Cosine of predictor heading angle	
$\cos\ \xi^V$	COSXI	CXIV	Cosine of vehicle heading angle	
$\sin\ \xi^V$	SINXI	SXIV	Sine of vehicle heading angle	
$\dot{\xi}^P$	KXDE5	DXIP	Rate of change of heading angle in predictor - radians/sec	
$\dot{\xi}^P_{prev}$	KXDPE5	DXIR	Previous value of predictor heading angle rate - radians/sec	
$\Delta\xi^A$	B(5)	(2)	Increment in heading angle betwen EMS and X-15 analog simulation coordinate systems - radians	
ρ^P	KR2E8	RHOP	Atmospheric density in predictor - slugs	
ρ^P_o	KR2E8	RHPI	Initial condition value of predictor atmospheric density - slugs	
ρ^P_{prev}	KR2E8	RHPR	Previous value of predictor atmospheric density	
ρ^V	RHOO	RHOO	Atmospheric density for vehicle - slugs	
τ	TRBS	TAU	Time constant in nondimensional GAA position coordinate filteres - sec	
$\tau_{\dot{H}^*}$	KTHDE2	KTAU	Time constant in nondimensional damping parameter filter - sec	60.
ϕ_c	KPHE1	PHIO	Constrained and damped bank angle command - degrees	
$\phi_{c\ell}$	KS5E1	S05T	Bank angle command after dynamic pressure limiting for control surface effectiveness - degrees	
ϕ_{max}	KS13E1	S13T	Constraint and damping modulated upper limit on bank angle - degrees	
$\phi_{max\ abs}$	K117E1	K12	Absolute upper limit on bank angle command - degrees	70.
$\phi_{max\ \ell}$	KPHXE1	PHIM	Limited value of ϕ_{max}	
ϕ_{mc}	KS5E1	S05T	Bank angle maneuver command - degrees	
$\phi_{mc\ lim}$	KSYE1	SYT	GAA polar angle limit on bank maneuver command - degrees	
ϕ_{mc/R_c^*}	(3)	(3)	Bank angle maneuver command due to cross range error - degrees	
ϕ_{nom}	K37E1	K3	Nominal value of constraint and damping modulated upper limit on bank angle - degrees	75.

TABLE 1 (CONT.)

Symbol			Description	Value (if constant)
Engineering	SDS 930	Alert		
ϕ^{P}	KPHE1	PHI	Final rate limited bank angle in predictor - degrees	
ϕ^{P}_{c}	KPHE1	PHI	Bank angle command for predictor prior to rate limiting - degrees	
ϕ^{P}_{mc}	KPHAE1	PHIA	Bank angle maneuver command for predictor - degrees	
ϕ^{P}_{prev}	PHICRP	PIPR	Previous value of rate limited predictor bank angle - degrees	
ϕ^{v}_{Bc}	PHICX	(3)	Body axis roll command for vehicle - degrees	
$\phi^{v}_{Bc\,rl}$	PHICR	PHRL	Rate limited body axis roll command for vehicle - degrees	
$\phi^{v}_{B\,prev}$	PHICRP	PHIR	Previous value of rate limited vehicle roll command - degrees	
ϕ^{v}_{c}	PHIC	PHIC	Bank angle command for vehicle prior to conversion to body axis roll command - degrees	
$\cos \phi^{P}$	KCPE3	CPHI	Cosine of ϕ^{P}	
$\sin \phi^{P}$	KSPE3	SPHI	Sine of ϕ^{P}	
$\cos \phi^{v}_{Bc}$	CPHIR	(3)	Cosine of ϕ^{v}_{Bc}	
$\sin \phi^{v}_{Bc}$	SPHIR	SPHR	Sine of ϕ^{v}_{Bc}	
$\dot{\phi}_{max}$	PRL7	1/KPH3	Maximum allowable roll rate of vehicle - degrees/sec	14.
$\Delta\phi_{max}$	DPX	DPHI	Maximum change in bank angle that rate limit will allow between updates	
$\Delta\phi_{AR*}$	(3)	(3)	Increment in bank angle maneuver command due to range errors if landing site is in aft end of GAA	

TABLE 2 LIST OF CODES

Symbol		Description
SDS 930	Alert	
IPH	IPH	EMS initialization code; 0 if not intitialized, 1 if initialized
IKEY	IKEY	Pilot controlled terminal energy code; 0 for low key terminal energy, 1 for high key
ITARG	ITAR	Pilot controlled landing site code; five values (1 to 5) corresponding the five available landing sites
IENG	IENG	Vehicle activated engine status code; 0 if engine is not firing, 1 if firing
KO	IKO	EMS vehicle status code; 0 if vehicle is assumed to be attached to the B-52, 1 if it is assumed to be dropped.
IFLAG	IFLAG	EMS status output code; 0 if EMS is operating, 1 if it is not
IEXT	IEXT	EMS GAA status code; 0 if no GAA has been predicted, 1 if it has
IRTGG	DOUT(8)	EMS landing site position output code; 0 if landing site is behind the X-15, 1 if it is ahead
ITIME	ITIM	EMS vehicle time code; 0 if time dependent filteres have not not been initialized, 1 if they have
ISS17	IS17	Vehicle activated drag brake position code; 0 if not deflected, 1 if deflected
KOPE	VKOX	EMS vehicle previous history code; 0 if no previous history is available for generating commands, 1 if it is
ICGS	ICGS	EMS constraint control subroutine useage code; 0 if used for vehicle, 1 if used for predictor
IPH	IPH	EMS predictor phasing code; 3 for maximum range prediction, 4 for minimum range prediction, 5 for cross range prediction
MODEB	IMDB	EMS prediction type code; -1 for maximum range, 0 for minimum range, 1 for cross range
IINIT	INIT	EMS input code; 0 if new inputs are available for predictor initial conditions, 1 if they are not
IDATA	IDAT	Hardware activated interrupt code; 0 if computational time is still available for prediction on current cycle, 1 if it is not
IPRED	IPRD	EMS predictor status code; 0 if predictor is ready to start a new prediction, 1 if current prediction was interrupted prior to completion
KODE	VKDE	EMS predictor previous history code; 0 if previous history is not available for generating commands, 1 if it is
MODEA	IMDA	EMS predictor stopping code; -1 for heading stop, 1 for energy stop
IRX	IRX	EMS maximum range prediction ready code; 0 if used to set up coefficients, 1 if not
IRN	IRN	EMS minimum range predictor ready code; 0 if used to set up coefficients, 1 if not
IRCX	IRCX	EMS cross range prediction ready code; 0 if used to set up coefficients, 1 if not
IKON	IKON	EMS coefficient set up procedure restart code; 0 if starting, non zero if started
IKON2	IKN2	EMS coefficient set up procedure counter; 0 if no coefficients set up, 3 if coefficients for one GAA set up, etc.
ISS27	IS27	Pilot controlled horizontal stabilizer deflection code; 0 if EMS is allowed to use full deflection, 1 if EMS is restricted to 75% of full deflection

V. REFERENCES

1. Anon.: An Energy Management System Design for Flight Testing in the X-15. Rept. No. 7176-935001, Bell Aerosystems Company, April 1963.

2. Cockayne, William G.: Program Manual on X-15 EMS Computer Programs for the SDS 930 Computer. Rept. No. 7237-927001, Bell Aerosystems Company, March 1966.